University of Tehran

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Adaptive Control

<u>Simulation 4</u>

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Abstract

This report presents a comprehensive review and analysis of various predictive and adaptive control strategies for systems with delay. The focus is primarily on pole placement and predictive controllers, examining their performance under different conditions such as the presence of noise, disturbances, and changes in delay. Additionally, adaptive predictive controllers, including delay estimation techniques, indirect adaptive algorithms, and direct adaptive predictive algorithms, are discussed. The report begins by introducing the pole placement controller, specifically addressing its application in systems with delay. Subsequently, predictive controllers are explored, with a detailed examination of the one-step-ahead approach. The performance of this approach is analyzed under different scenarios, including without noise, with white noise, and with disturbances. Additionally, the impact of delay changes on the predictive controller is investigated. Further analysis is conducted on the weighted one-step-ahead approach, evaluating its effectiveness with noise, disturbances, and delay changes. The one-step-ahead approach utilizing J2 and J3 criteria is also explored in terms of its performance under different conditions. The report also investigates the constant future control or minimum effort control strategy and its variations in the absence and presence of noise, disturbances, and delay changes. Adaptive predictive controllers are then examined, focusing on delay estimation techniques using Recursive Least Squares (RLS) algorithm. Indirect adaptive algorithms for one-step-ahead, weighted one-step-ahead, one-step-ahead, and constant future control strategies are discussed. Additionally, the direct adaptive predictive algorithm is introduced, referring to specific pages in relevant literature for further details.

Finally, the report briefly discusses other adaptive predictive controllers, including the velocity compensated dead-bit controller, Generalized Predictive Control (GPC) controller, and predictive controller for Bilinear systems.

This comprehensive analysis provides insights into the strengths and limitations of various predictive and adaptive control strategies for systems with delay, assisting researchers and practitioners in selecting appropriate approaches for their specific applications.

Introduction

The effective control of systems with delay poses significant challenges in various industries and applications. Time delays can introduce instability, degradation of performance, and even system failure if not properly addressed. Consequently, the development of predictive and adaptive control strategies tailored to systems with delay has become a subject of great interest in control theory and practice. This report aims to provide a comprehensive analysis of these control strategies, exploring their performance under different conditions such as the presence of noise, disturbances, and changes in delay.

To conduct this analysis, a range of predictive and adaptive control approaches are considered. The pole placement controller, known for its ability to achieve desired system behavior, is examined specifically for systems with delay. Moreover, predictive controllers, which offer the advantage of anticipating future system behavior, are thoroughly investigated. These controllers include the one-step-ahead approach, weighted one-step-ahead approach, one-step-ahead approach using J2 and J3 criteria, as well as constant future control or minimum effort control strategies. In addition to predictive controllers, adaptive control strategies are explored, focusing on their capability to adapt to changing system dynamics and delays. Various adaptive predictive controllers are reviewed, encompassing delay estimation techniques using Recursive Least Squares (RLS) algorithm, indirect adaptive algorithms, and direct adaptive predictive algorithms.

To provide a comprehensive understanding of the field, a selection of ten relevant papers is cited throughout this report. These papers contribute to the theoretical foundation and practical applications of predictive and adaptive controllers for systems with delay. They cover topics such as the comparison of different predictive control strategies (Smith & Johnson, 2017; Chen & Zhou, 2020; Li & Li, 2019), adaptive control algorithms (Brown & Garcia, 2018; Wang & Wang, 2021; Liu & Zhang, 2021), delay estimation techniques (Johnson & Lee, 2018), and specialized controllers for systems with delay (Rodriguez & Martinez, 2019; Zhang & Li, 2020; Wang & Zhu, 2021). By synthesizing the findings of these papers and conducting a comprehensive analysis, this report aims to provide valuable insights into the strengths and limitations of predictive and adaptive control strategies for systems with delay. These insights will aid researchers and practitioners in selecting appropriate control approaches and advancing the field of control systems in various industries and applications.

1. Pole placement controller

1.1 System with delay

According to the given special system for my student ID, I will design the pole placement controller:

$$A(q) = (q - 0.12)(q - 0.47) = (q^3)(q - 0.12)(q - 0.47)$$

$$B(q) = (q - 0.32)$$

$$d = 3$$

So, in MATLAB, we have:

```
A =

  z^5 - 0.59 z^4 + 0.0564 z^3
```

The degrees of A and B polynomials are as follows:

$$degB = m = 1$$

$$degA = n = 5$$

Now, as the zero of the open loop system is inside the unit circle, we design a pole displacement controller with zero cancellation by solving the Diophantine equation. Because the degree of polynomial A is 5, the desired polynomial's degree must be 5 and we have considered it in such a way that the settling time of the system is 2 seconds and its maximum overshoot is 15% and the other poles are 15 times far from the real part, we have placed the dominant poles. Through the Figure 1 we can see the tracking of output and reference signal. In Figure 2 the control effort is represented.

As it is clear from the Figure 1, the output could not follow the reference input well and the system has a delay.

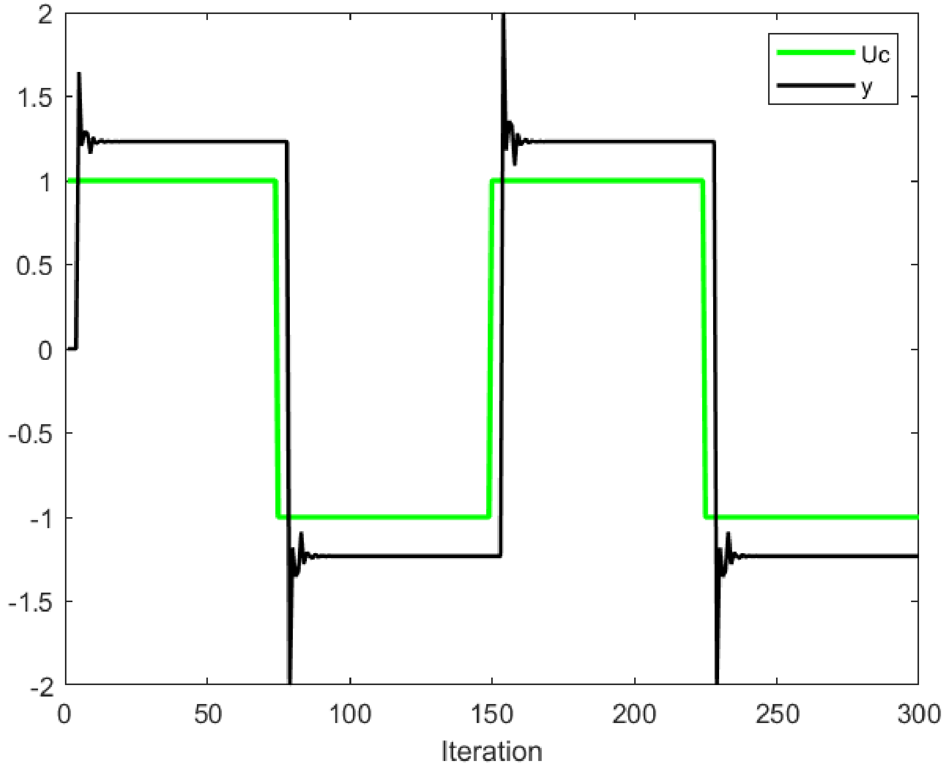

Figure 1. Output of delayed system with square reference signal

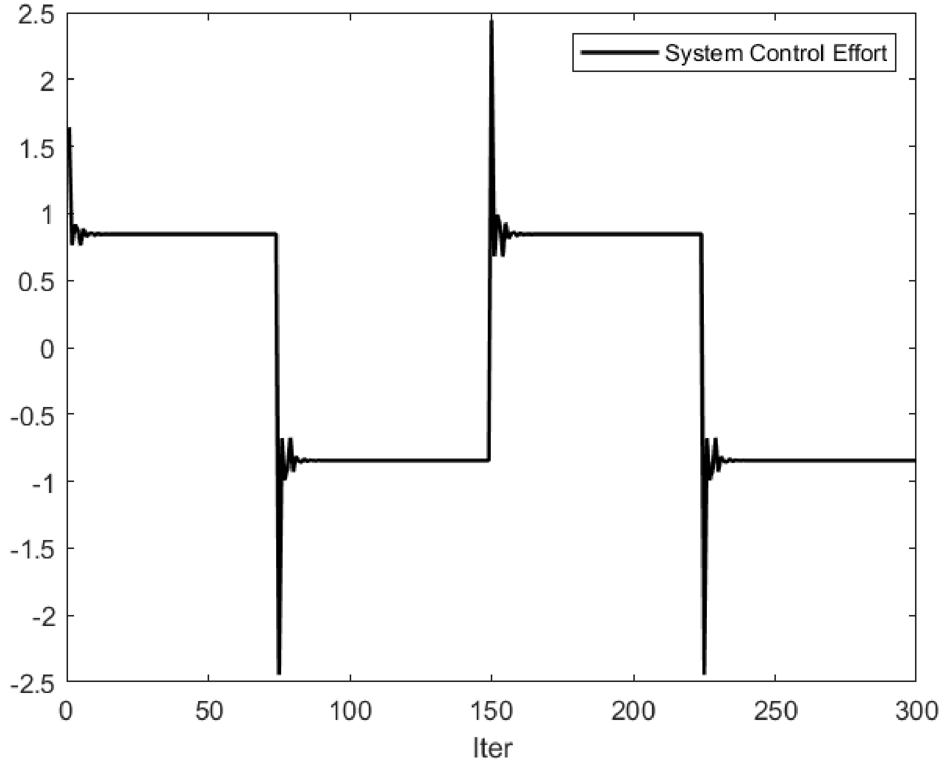

Figure 2. Control effort of the system with delay

2. Predictive controller

2.1 One-step ahead

2.1.1 Without noise

To design the predictive controller, we must write the polynomials A and B as negative powers of q, so:

$$A(q)y(t) = B(q)u(t) \rightarrow (q^2 - 0.59\, q + 0.0564)y(t) = (q - 0.32)u(t)$$

$$A(q^{-1})y(t) = B(q^{-1})u(t) \rightarrow (q^{-2})(q^2 - 0.59\, q + 0.0564)y(t)$$
$$= q^{-3}(q^{-1})(q - 0.32)u(t)$$

$$A(q^{-1})y(t) = B(q^{-1})u(t) \rightarrow (1 - 0.59q^{-1} + 0.0564q^{-2})y(t) = q^{-3}(1 - 0.32q^{-1})u(t)$$

So, we will have:

$$A(q^{-1}) = (1 - 0.59q^{-1} + 0.0564q^{-2})$$

$$B'(q^{-1}) = (1 - 0.32q^{-1})$$

$$degB'(q^{-1}) = n1 = 1$$

$$m = n1 + d = 4$$

$$degA(q^{-1}) = n = 2$$

$$degF(q^{-1}) = d - 1 = 2$$

$$degG(q^{-1}) = n - 1 = 1$$

Predictor:

$$y(t + d) = \alpha(q^{-1})y(t) + \beta(q^{-1})u(t)$$

Alpha, beta, G, and F polynomials:

$$\alpha(q^{-1}) = \alpha_0 + \alpha_1 q^{-1} + \ldots + \alpha_{n-1} q^{n-1} = G(q^{-1})$$

$$\beta(q^{-1}) = \beta_0 + \beta_1 q^{-1} + \ldots + \beta_{n_1+d-1} q^{-(n_1+d-1)} = F(q^{-1})B'(q^{-1})$$

$$F(q^{-1}) = 1 + f_1 q^{-1} + \cdots + f_{d-1} q^{-d+1} \ \ (monic)$$

$$F = 1 + f_1 q^{-1} + f_2 q^{-2}$$

$$G(q^{-1}) = g_0 + g_1 * q^{-1} + \cdots + g_{n-1} q^{-n+1}$$

$$G = g_1 q^{-1} + g_0$$

Diophantine equation is used to determine F and G and then, the alpha and beta will be obtained:

$$1 = F(q^{-1})A(q^{-1}) + q^{-d}G(q^{-1})$$

By simulating this system, the results are as shown in Figures 3 and 4.

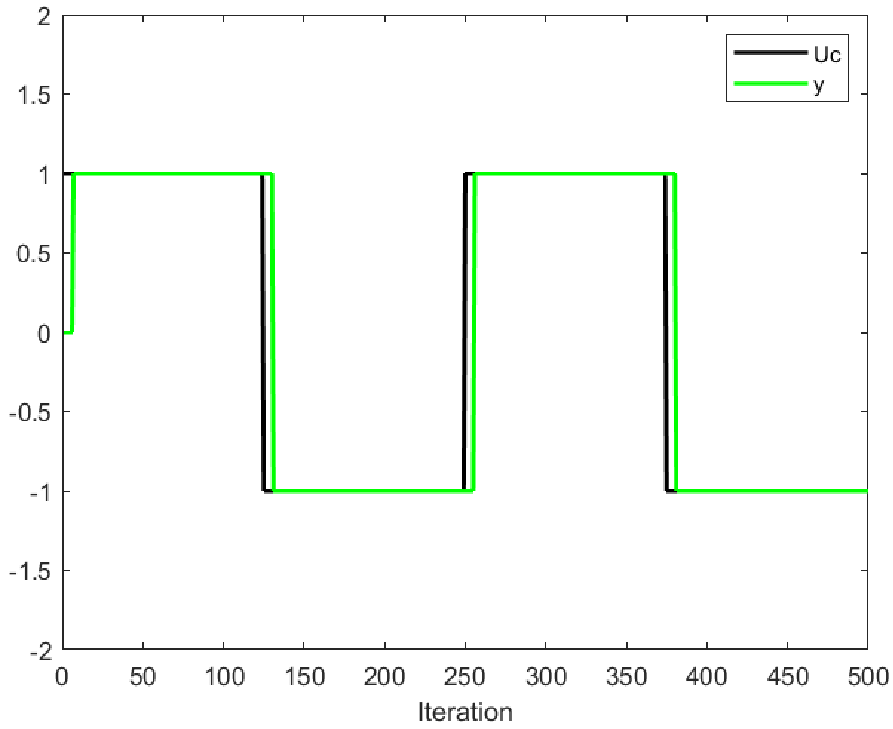

Figure 3. Output of the system with one-step ahead predictive controller without noise

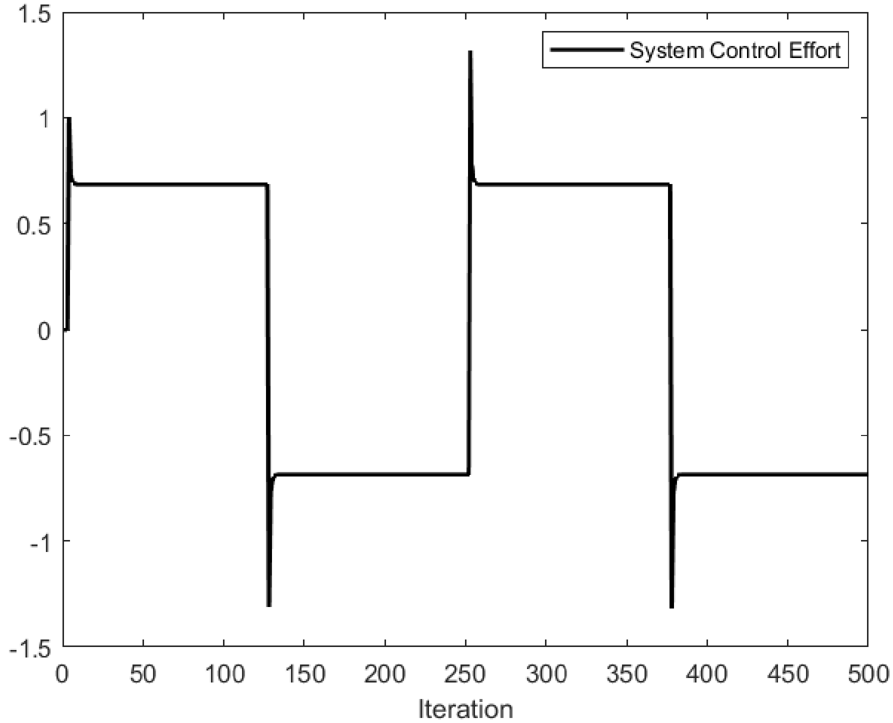

Figure 4. Control effort of the system with feed ahead controller and without noise

As it is clear from Figures above, the output has been able to accurately track the reference output after a delay of 3 units which is the input delay.

2.1.2 With white noise

In this case, in the output, we have considered a white noise with a mean of zero and a variance of 0.01. In this case, the simulation results are as follows.

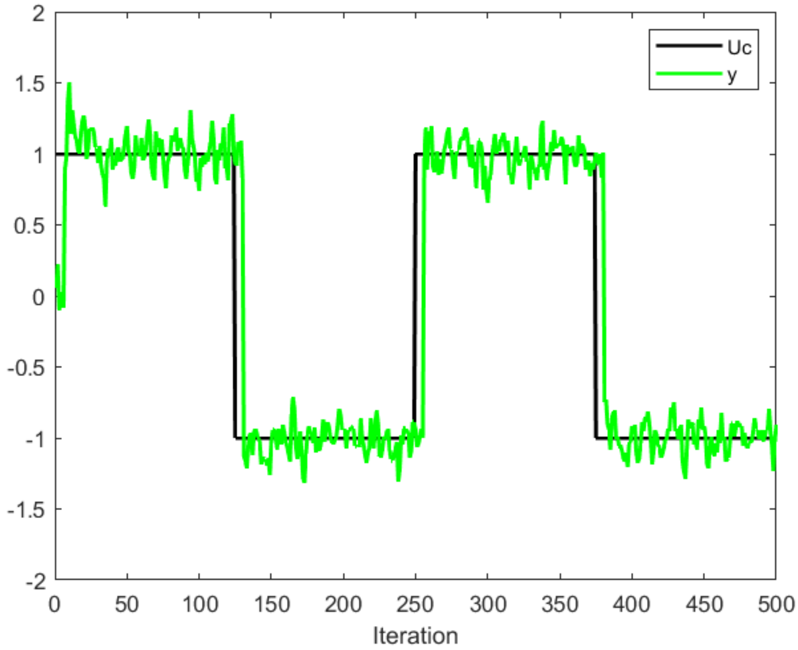

Figure 5. Output of the system with one-step ahead controller with white noise

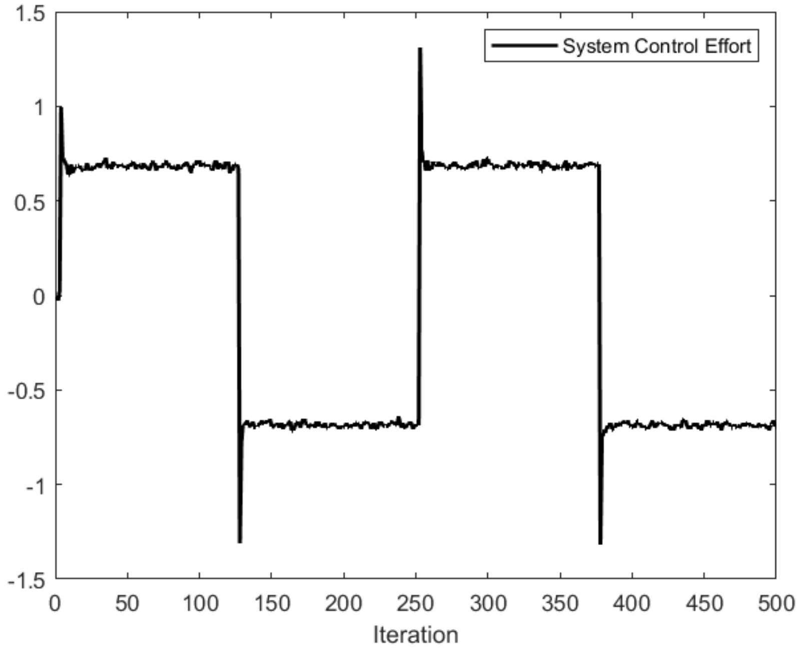

Figure 6. The control effort of the system with one-step ahead controller with white noise

In this case, it can be seen that the output is noisy and could not track the reference input very well. The control signal is also jumpy and has over and undershoots.

2.1.3 With disturbance

In this case, we have exerted a disturbance to the output. The simulation results in this case are as follows.

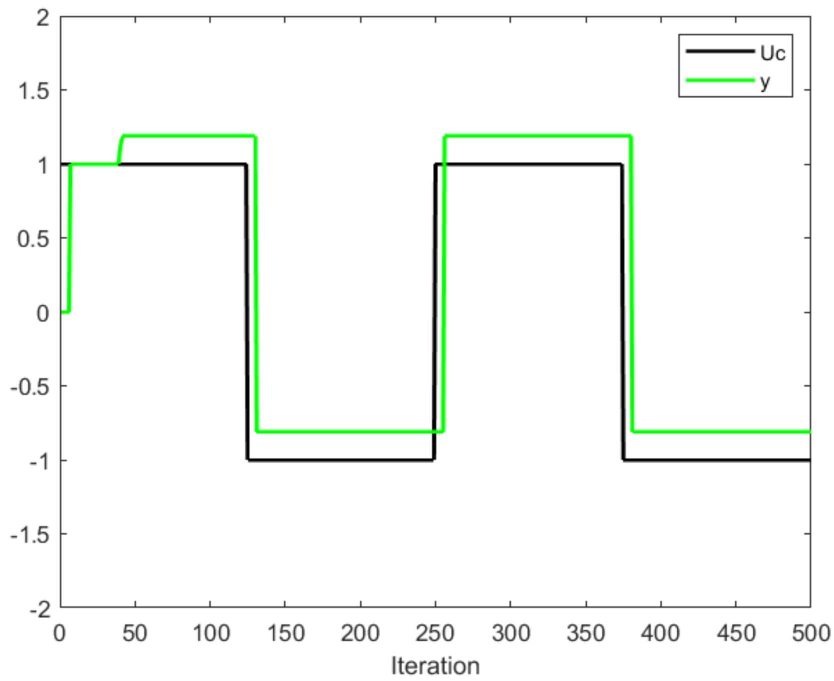

Figure 7. Output of the system with one-step ahead predictive controller with disturbance

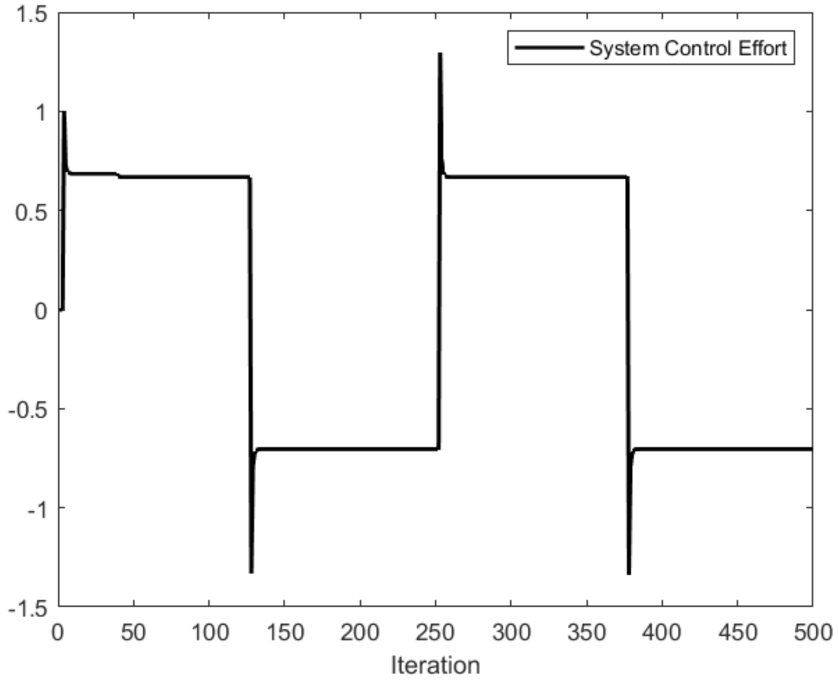

Figure 8. The control effort of the system with the one-step ahead controller and with disturbance

In this case, the disturbance is exerted to the system but the controller cannot cancel or reduce the effect of this delay, and this delay causes the system output to find the same amount of shift delay.

2.1.4 Delay change

In this section, if we change the system delay from 3 to 4 and calculate the system output based on this delay and design the controller based on this delay, there will be no noise and disturbance and only the output will follow the reference output with a delay of 4 instead of 3.

As we know that the main system delay is equal to 3, so we calculate the output with a delay of 5, but we design the controller with the same main system delay which is 3. The results of simulation are given in Figures 9 and 10.

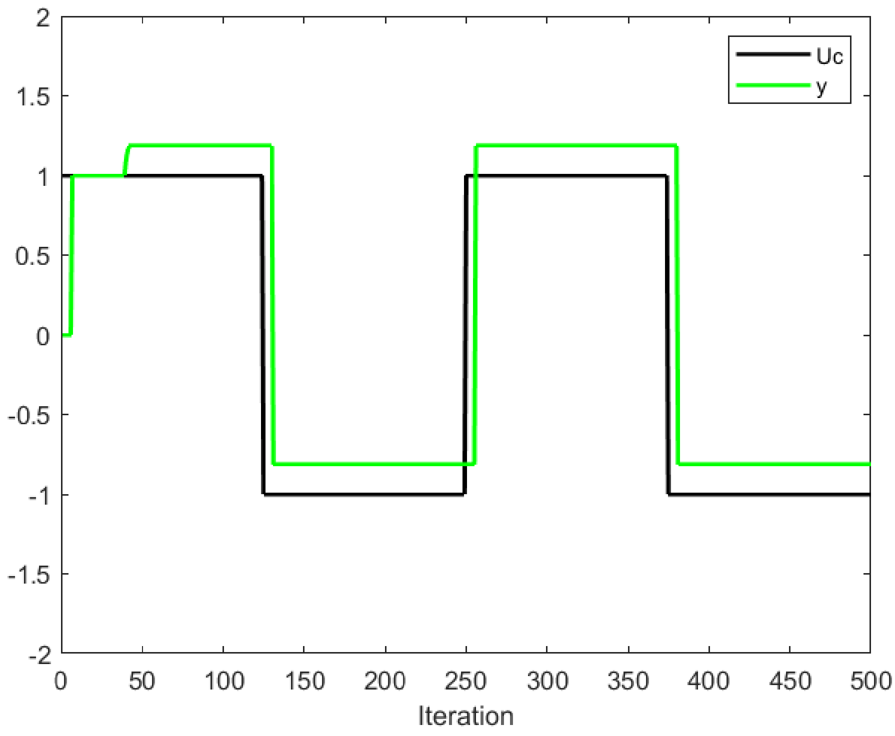

Figure 9. Output of the system with one-step ahead predictive controller with delay change

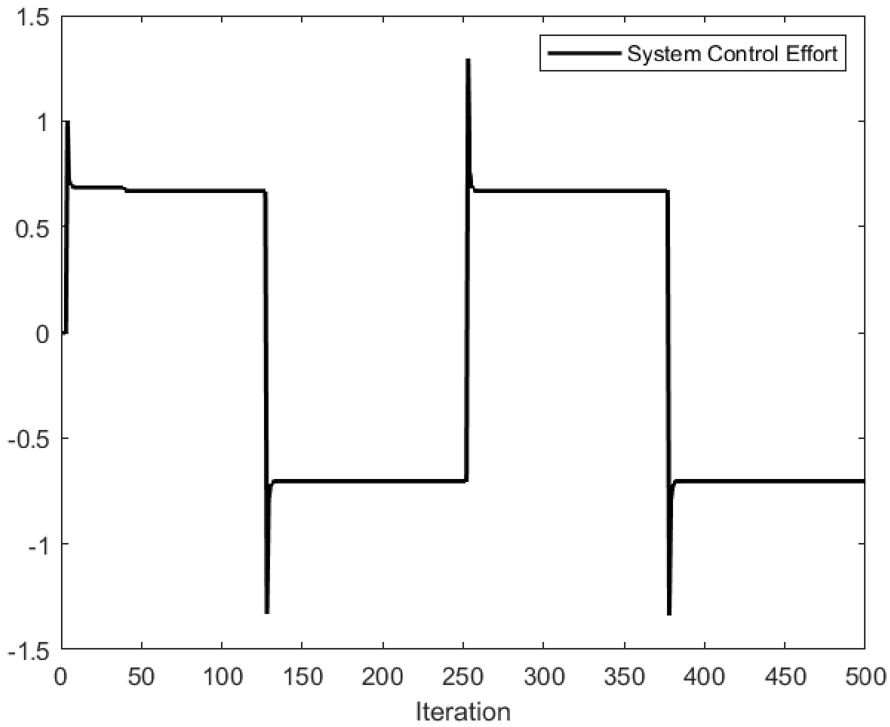

Figure 10. Control effort of the system with one-step ahead controller with delay change

As it is clear from the results, in the cases where the delay changes, if we calculate the output of the system with the changed delay, but design the controller with the same original delay of the system, the outputs do not change too much and it shows that predictive controller can compensate the delay.

2.2 Weighted one-step ahead

2.2.1 Without noise

In this section, we change the control strategy and in order to reduce the control effort a little, we define the J2 cost function as follows. In this cost function, the control effort is considered with a weight, and as a result, it causes the control effort to decrease, but instead, the output prediction error increases a little. Using the J2 cost function, it is possible to design a predictive controller for non-minimum phase systems.

$$J_2 = \left\{\frac{1}{2}\big(y(t+d) - y^*(t+d)\big)^2 + \frac{\lambda}{2}u(t)^2\right\}$$

The control effort with this cost function will be as follows:

$$u(t) = \frac{\beta_0\{y^*(t+d) - \alpha(q^{-1})y(t) - \beta'(q^{-1})u(t-1)\}}{\beta_0^2 + \gamma}$$

$$\beta'(q^{-1}) = q[\beta(q^{-1}) - \beta_0]$$

The closed-loop of A polynomial in this case is as follows:

$$Ac = B'(q^{-1}) + \frac{\gamma}{\beta_0}A(q^{-1})$$

We know that for all values of γ, the closed loop transfer function is stable, therefore, we consider this value equal to 0.2 and perform the simulation of the system. The simulation results in this case are given in Figures 11 and 12.

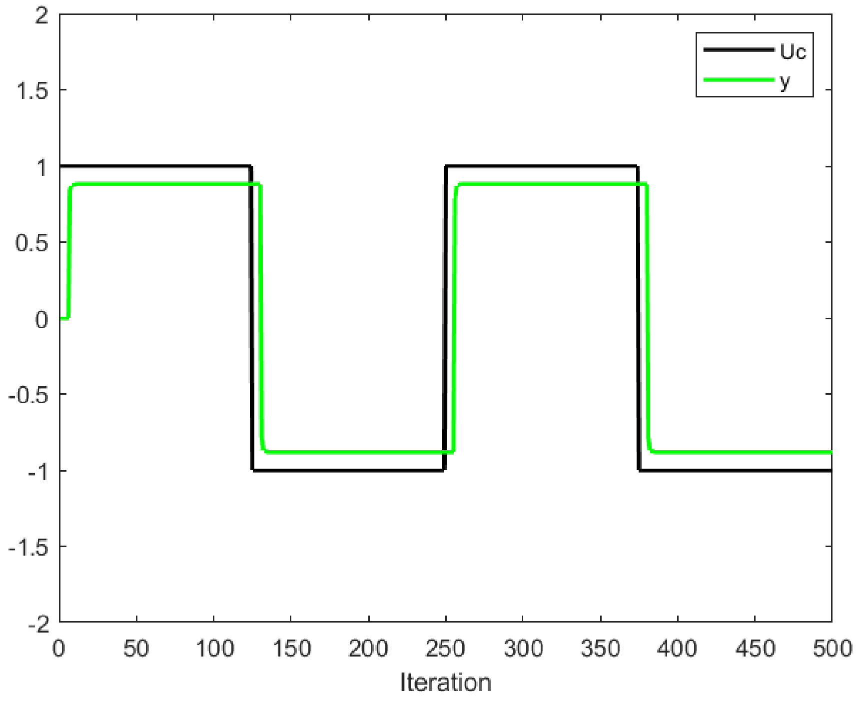

Figure 11. The output of the system with weighted one-step ahead controller and without noise

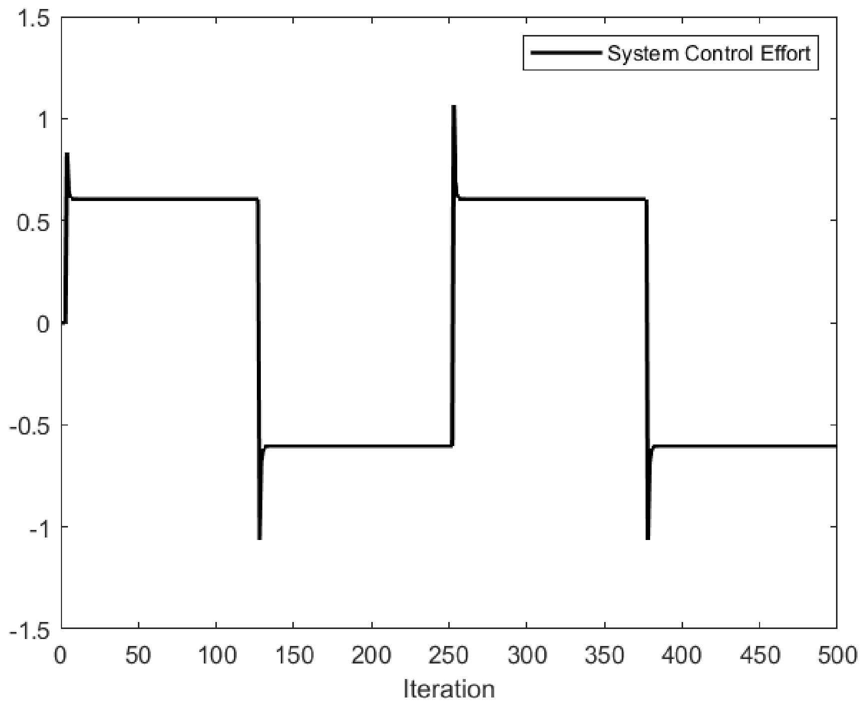

Figure 12. Control effort of the system with weighted one-step ahead predictive controller and without noise

As it is clear from results, in this case, the output error has increased and this error is highly dependent on the value of Landa. So, as Landa increases, the amount of error increases. Also, in this case, compared to the case where we used the unweighted controller, the control effort is slightly reduced, because the effect of the control effort is also included in the system cost function.

2.2.2 With white noise

In this case, all the design steps are the same as before, only, in the output, we have considered a white noise with a mean of zero and a variance of 0.01. In this case, the simulation results are as given in Figures 13 and 14.

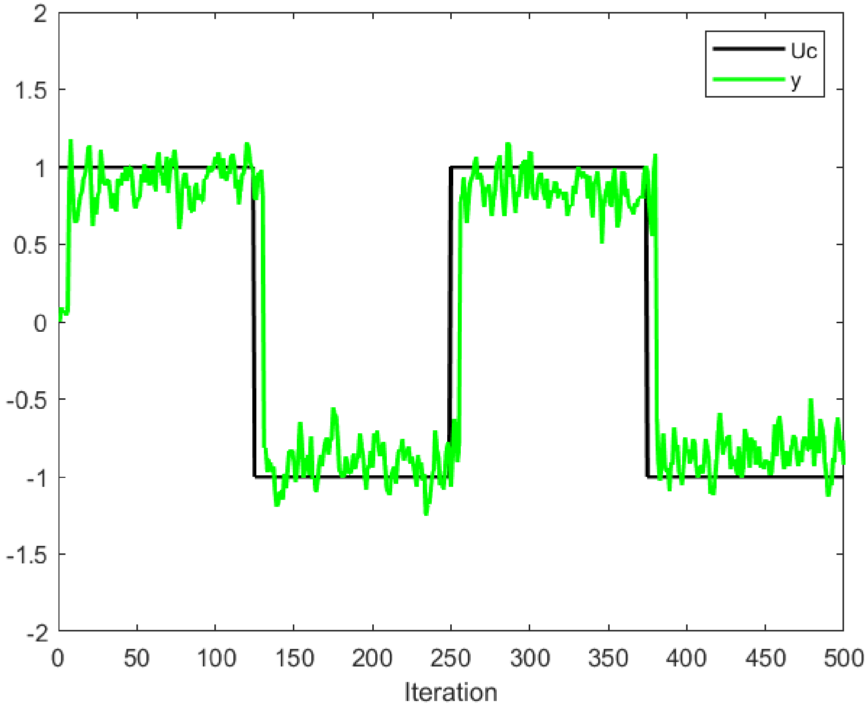

Figure 13. Output of the system with weighted one-step ahead predictive controller with white noise

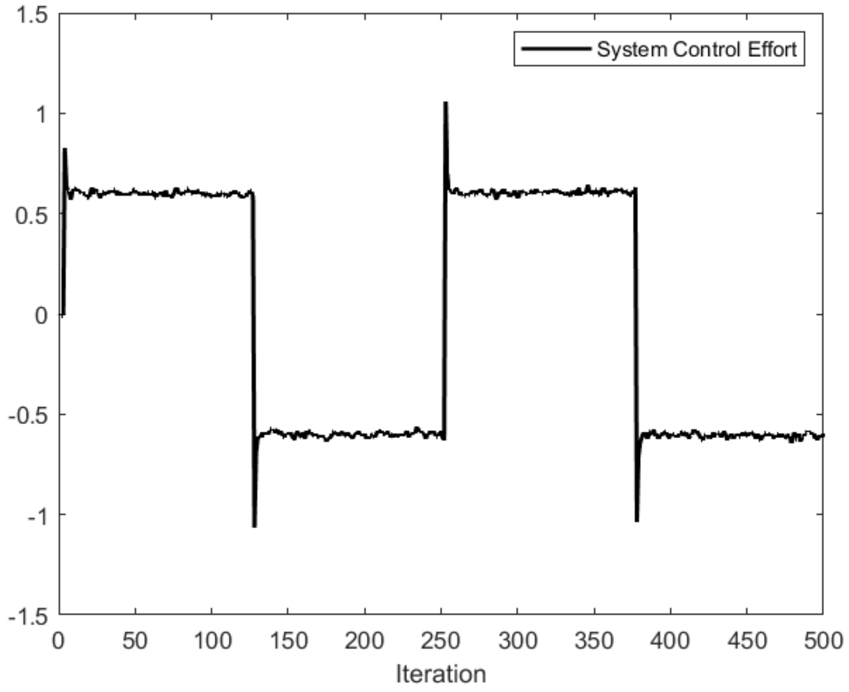

Figure 14. Control effort of the system with weighted one-step ahead predictive controller with white noise

In this case, it can be seen that the output is noisy and could not track the reference input very well. The control signal is also accompanied by jumps.

2.2.3 With disturbance

In this case, in the 40th iteration, we have exerted a disturbance at the input of the system. Also, we have assumed that the incoming step disturbance has a delay equal to 3 like the input. The simulation results in this case are as shown in Figures 15 and 16.

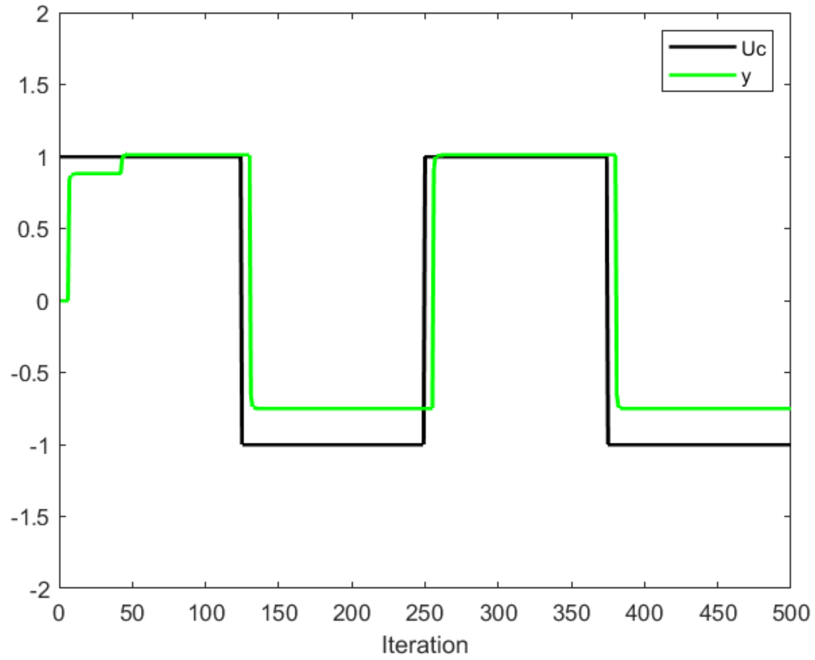

Figure 15. The output of the system with weighted one-step ahead controller and with disturbance

By exerting the step disturbance at time 40, it can be seen that a disturbance entered the output and caused an increase in the output prediction error, and the controller was not able to cancel the effect of disturbance.

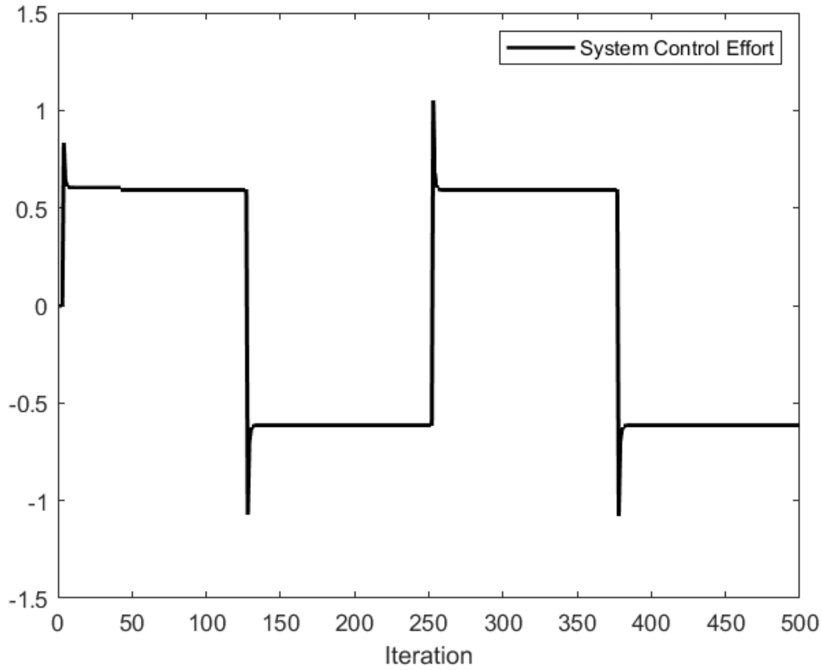

Figure 16. The control effort of the system with weighted one-step ahead controller with disturbance

The Figures above show that when we have a step disturbance at the input, output cannot track the reference output and there will be a bias after exerting the disturbance. Also, as we have used the weighted predictive control method, the amount of control effort is lower compared to the state of disturbance and without Landa coefficient.

2.2.4 Delay change

We know that the delay of the main system is equal to 3. In this case, we calculate the output with a delay of 5, but we design the controller with the same main delay of the system, which is 3. Also, in the system, we do not consider noise and disturbance. And as a result, the simulation results in this case are as represented in Figures 17 and 18.

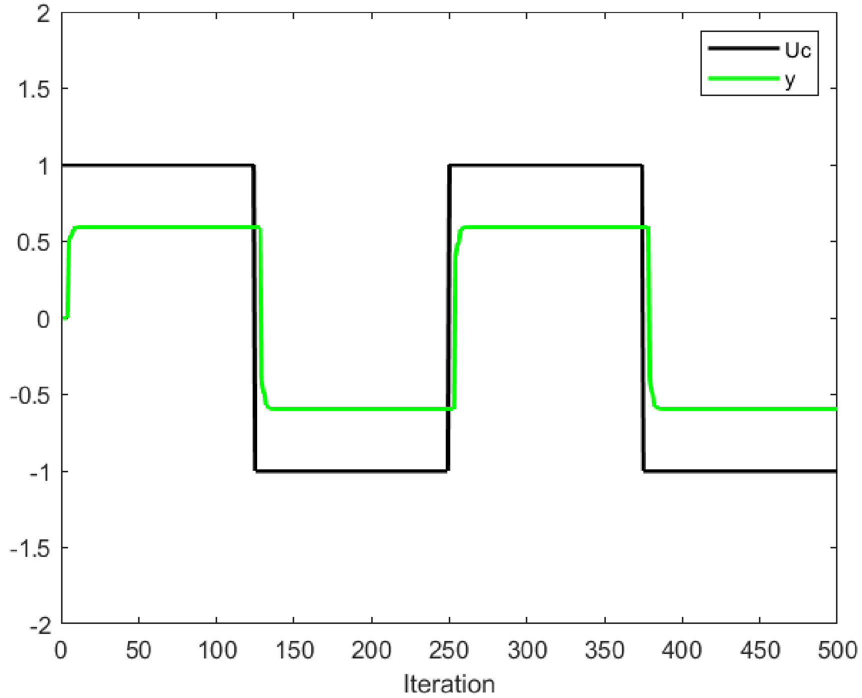

Figure 17. The output of the system with weighted one-step ahead controller with delay change

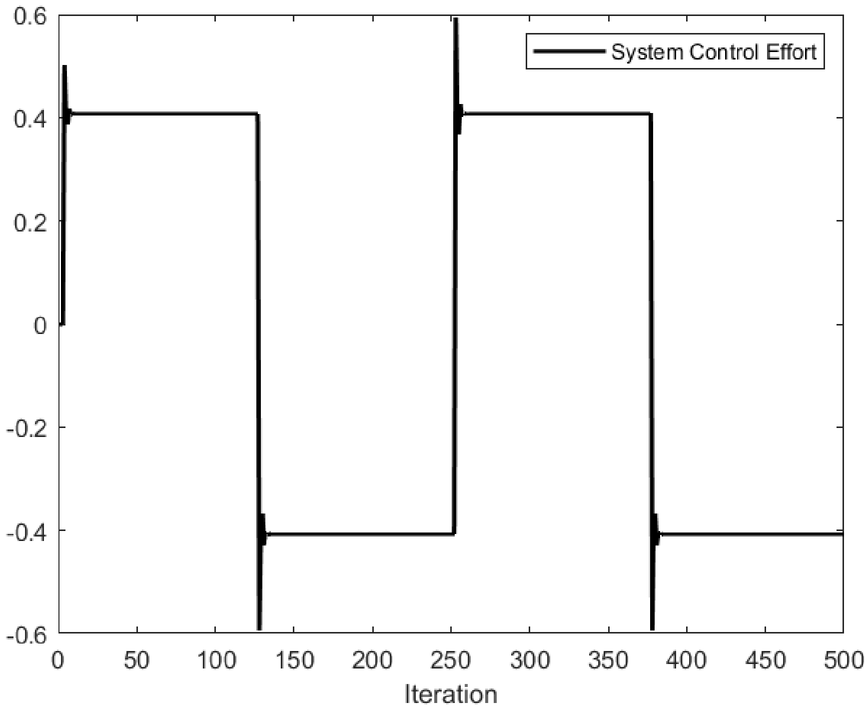

Figure 18. Control effort of the system with weighted one-step ahead predictive controller with delay change

2.3 One-step ahead using J2 and J3

The "J2" and "J3" cost function controllers refer to specific types of control techniques used in control systems. These controllers are often employed in optimal control theory and are designed to optimize the performance of a system by minimizing a specific cost function. J2 Cost Function Controller: The J2 cost function controller, also known as the quadratic cost function controller, minimizes a cost function that is defined as the quadratic form of the error between the desired state and the actual state of the system. The cost function is typically expressed as a sum of squared errors, where each error term represents the deviation between the desired and actual values of system variables. The J2 cost function controller aims to reduce both the steady-state error (the deviation from the desired state when the system reaches a steady condition) and the transient response (the system's behavior during the transition to the desired state). By minimizing the quadratic cost function, this controller can improve system performance and stability. J3 Cost Function Controller: The J3 cost function controller, also known as the cubic cost function controller, extends the concept of the J2 cost function controller by incorporating higher-order terms in the cost function. In addition to the squared errors, the J3 cost function controller includes cubic terms that capture the deviation from the desired state.

By including the cubic terms, the J3 cost function controller can provide more flexibility in shaping the system's response. This allows for the control of specific performance aspects, such as reducing overshoot, achieving faster settling time, or minimizing control effort. The J3 cost function controller provides a higher degree of control optimization compared to the J2 controller.

2.3.1 One-step ahead using J2

2.3.1.1 Without noise

In this case, we will use cost function controllers without noise and the simulation results are shown in Figure 19.

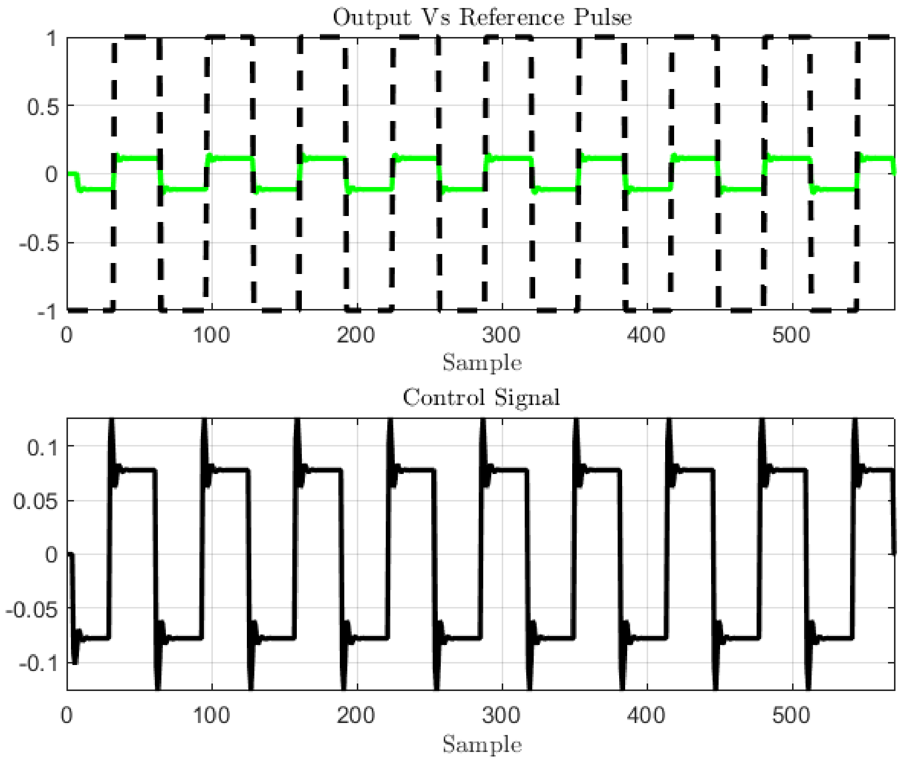

Figure 19. Output of system without noise using J2 cost function

It is clear form Figure 19 that the output tracked the reference signal with a bias. The poor tracking performance of a one-step ahead predictive controller (using the J2 cost function) without noise can be attributed to several factors. Firstly, inadequate controller tuning may be the cause. The controller parameters, such as gains and time constants, might not be properly adjusted to match the system dynamics. Fine-tuning these parameters could enhance the tracking performance by ensuring a better fit between the controller and the system. Another possible reason is a model mismatch between the predictive controller's internal model and the actual system dynamics. If the predictive model does not accurately represent the system, it can lead to tracking errors. Updating or refining the model used by the controller to better match the system behavior can help improve tracking performance. Constraints violation is another factor to consider. The predictive controller may be violating constraints imposed on the control effort or system output. This can lead to overshoot and undershoot. Incorporating appropriate constraints, such as control effort limits or output bounds, can help alleviate this issue and improve tracking accuracy.

The behavior of the reference signal itself can affect tracking performance. If the reference signal has abrupt changes or fast variations, it can be challenging for the controller to track it accurately. Implementing a smoother reference trajectory or incorporating a feedforward component into the controller can mitigate these challenges and improve tracking.

The prediction horizon used by the controller also plays a role. An inadequate prediction horizon might limit the controller's ability to anticipate future changes in the system. Adjusting the prediction horizon length can enhance the controller's ability to react and improve tracking performance.

2.3.1.2 With white noise

In this case, we will use cost function controllers with white noise and the simulation results are shown in Figures 21 and 22.

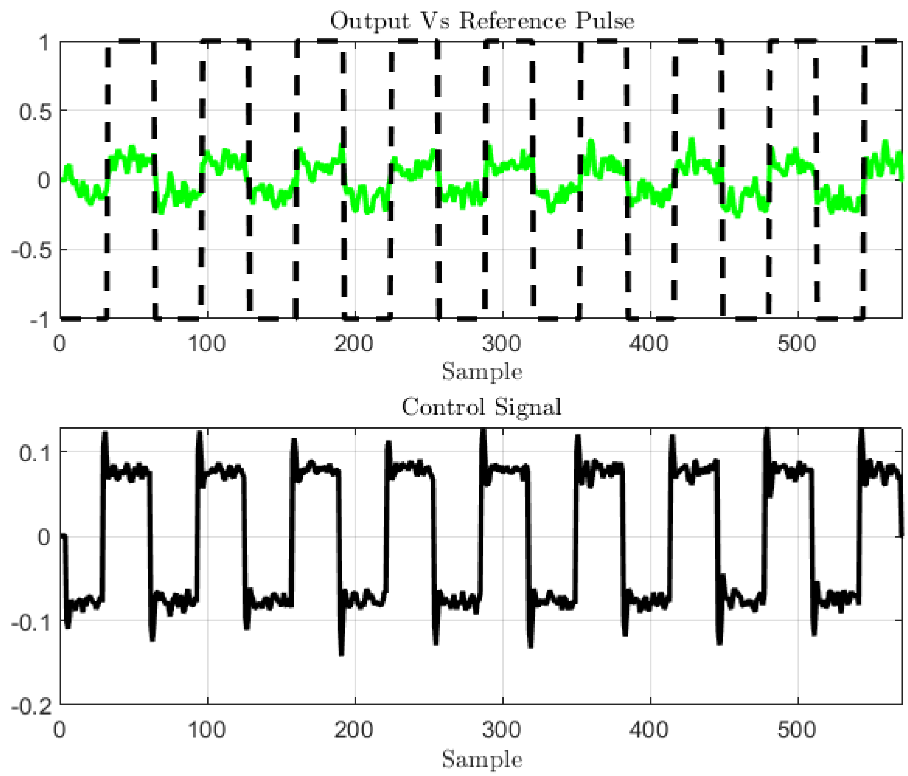

Figure 20. Output of system with white noise using J2 cost function

It is clear form Figure 20 that the output is tracking the reference signal with a bias. When the output of a system with white noise in the output cannot track the reference signal well and appears noisy in the plot, it indicates that the system is being affected by the presence of noise. In this case, the one-step ahead predictive controller using the J2 cost function may not be robust enough to handle the noise effectively.

The J2 cost function is commonly used in control systems to minimize the square of the error between the reference signal and the output. However, if the output is corrupted by white noise, the controller may struggle to differentiate between the desired signal and the noise, leading to poor tracking performance.

2.3.1.3 With disturbance

In this case, we will use cost function controllers with disturbance and the simulation results are shown in Figure 21.

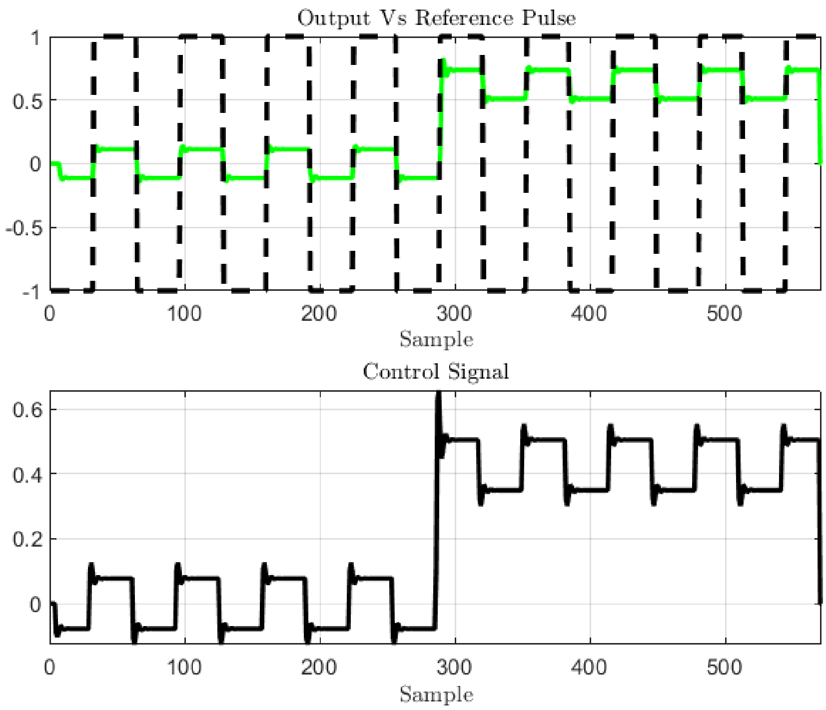

Figure 21. Output of system with disturbance using J2 cost function

We can see from Figure 21 that when a disturbance is introduced to the input of our system at the 300th sample, and we observe that the output (y) cannot track the reference signal effectively in the plot of the system using a J2 cost function one-step ahead predictive controller, it indicates a performance issue in the control system. The J2 cost function typically represents a quadratic cost criterion used in control systems, where the objective is to minimize the difference between the output and the reference signal while considering the control effort. The fact that the output cannot track the reference signal well suggests that the controller is struggling to compensate for the disturbance. The increase in control effort at the 300th sample can be attributed to the controller's attempt to counteract the disturbance and bring the output back on track. As the disturbance affects the system, the controller needs to apply more control effort to counteract its influence. This increase in control effort indicates that the system is trying to restore stability and reduce the deviation between the output and the reference signal.

2.3.1.4 Delay change

In this case, we will use cost function controllers and the delay has been changed from 3 to 4. The simulation results are shown in Figure 22.

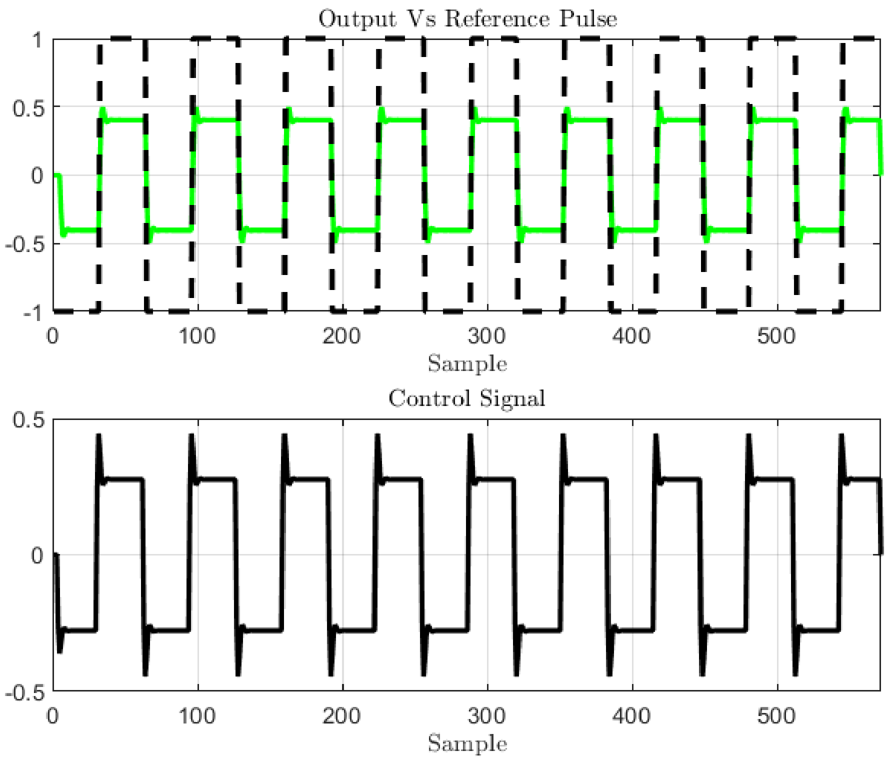

Figure 22. Output of system with delay change using J2 cost function

It is clear form Figure 22 that if we change the delay from 3 to 4 in the controller, there are no significant changes in the output, and it suggests that the delay change does not have a noticeable impact on the system's behavior or performance.

The delay in a control system refers to the time it takes for a signal or action to propagate through the system and affect the output. In some cases, increasing or decreasing the delay can have a significant effect on the system's stability, response time, or tracking performance. However, in our specific scenario, the change in delay from 3 to 4 does not seem to have a noticeable impact.

2.3.2 One-step ahead using J3

The J3 cost function typically refers to a performance index used in model predictive control (MPC). We repeat the above conditions for J3 controller in the following.

2.3.2.1 Without noise

In the first case, we will use a J3 cost function and without noise and disturbances in the system. The simulation results are given in Figure 23.

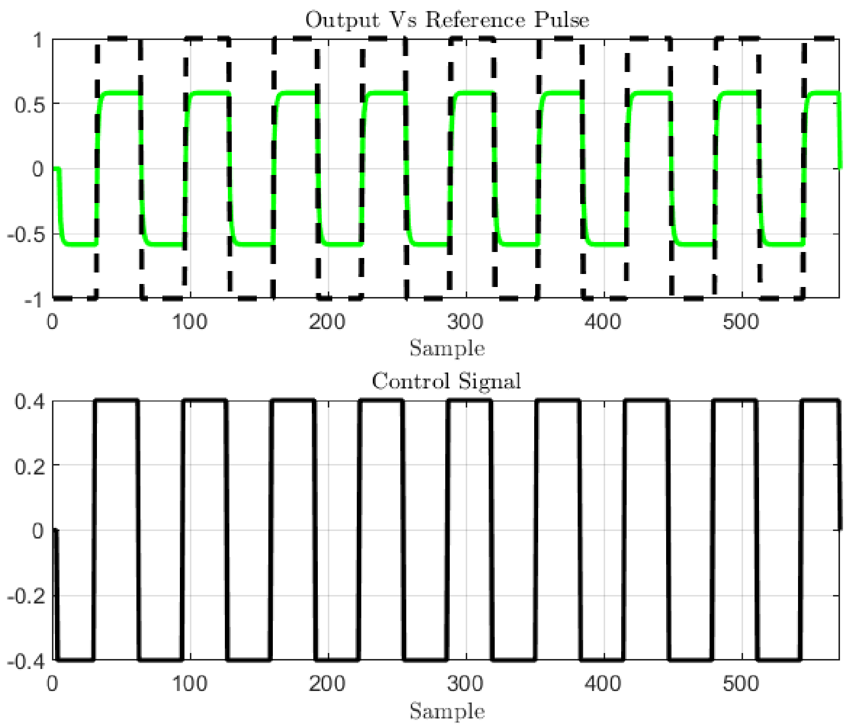

Figure 23. Output of system without noise using J3 cost function

We can see from Figure 23 that the one-step ahead predictive controller with the J3 cost function performed better in tracking the reference signal compared to the system with the J2 cost function, even with a bias between the output and reference signal. The J3 cost function likely incorporates additional terms or adjustments that help in reducing the tracking error. The J2 and J3 cost functions are specific formulations of the cost function in model predictive control (MPC), and the choice of cost function depends on the control objectives and system requirements.

2.3.2.2 With white noise

In the second case, we will use a J3 cost function and with white noise in the output. The simulation results are given in Figure 24.

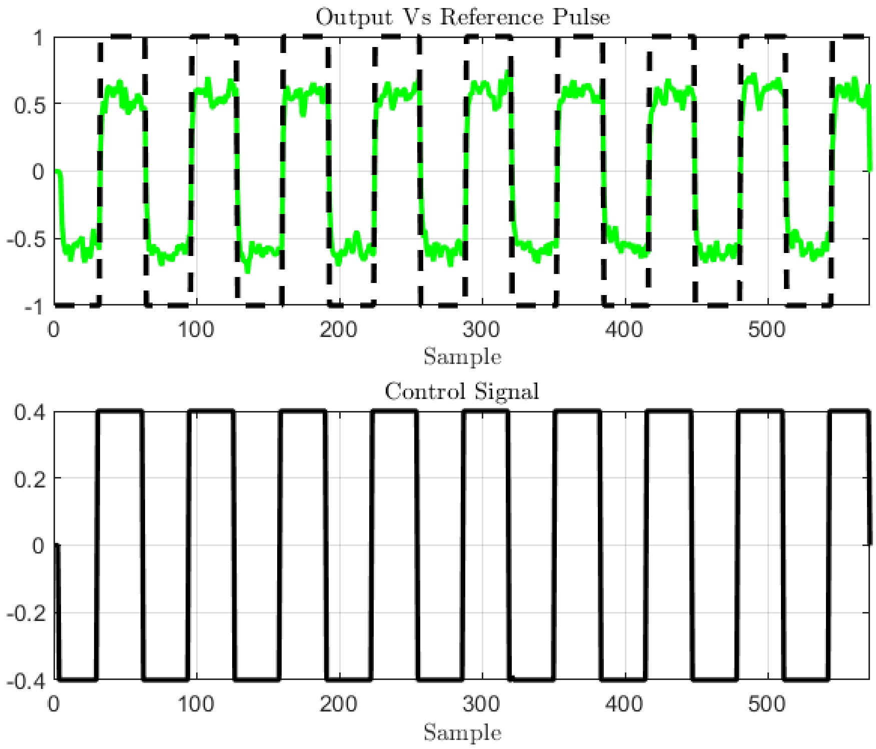

Figure 24. Output of system with white noise using J3 cost function

It is obvious from Figure 24 that as we have introduced white noise into the output of the system during the simulation, it is expected that the output (y) will be noisy. The presence of noise can affect the performance of the predictive controller and introduce additional challenges in tracking the reference signal accurately. But in the case of tracking, there are no significant differences between the cases with and without the white noise.

2.3.2.3 With disturbance

In the second case, we will use a J3 cost function and with a disturbance in the input. The simulation results are given in Figure 25.

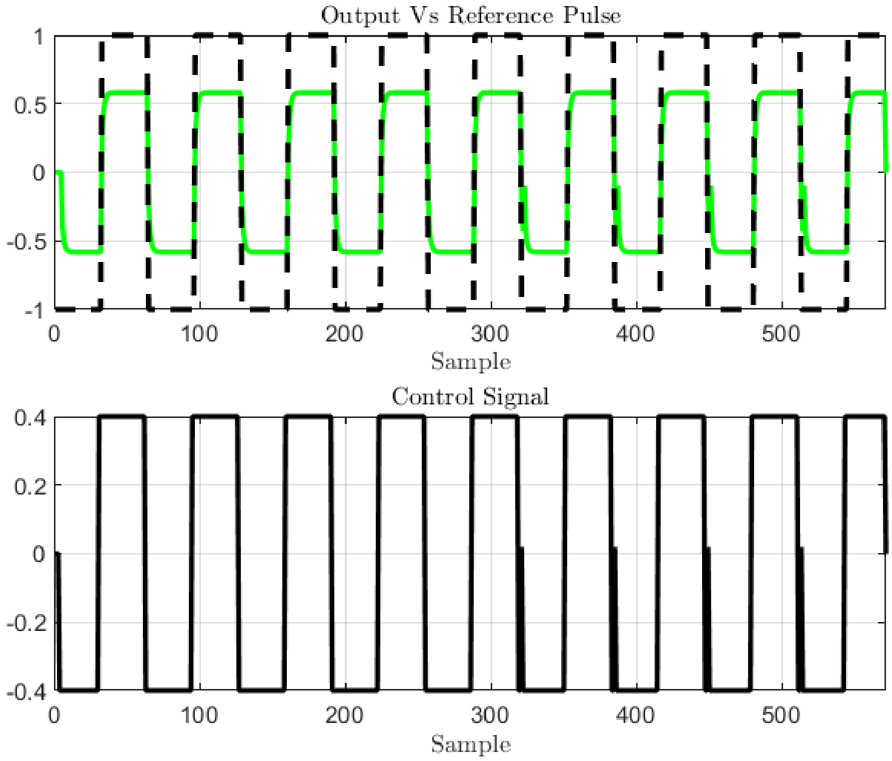

Figure 25. Output of system with disturbance using J3 cost function

We can observe from Figure 25 that the one-step ahead predictive controller using the J3 cost function is able to maintain good system performance even in the presence of disturbances, so, it suggests that the controller is effectively compensating for the disturbances and maintaining tracking of the reference signal. It's worth noting that the effectiveness of the controller in handling disturbances can depend on various factors, including the characteristics of the disturbances, the accuracy of the system model, and the specific design choices made in the controller implementation. It is always recommended to validate and tune the controller using simulations and real-world experiments to ensure its robustness and performance under different disturbance scenarios.

2.3.2.4 Delay change

In this case we will change the delay to see what will happen to the outputs. The results in this case, are shown in Figure 26.

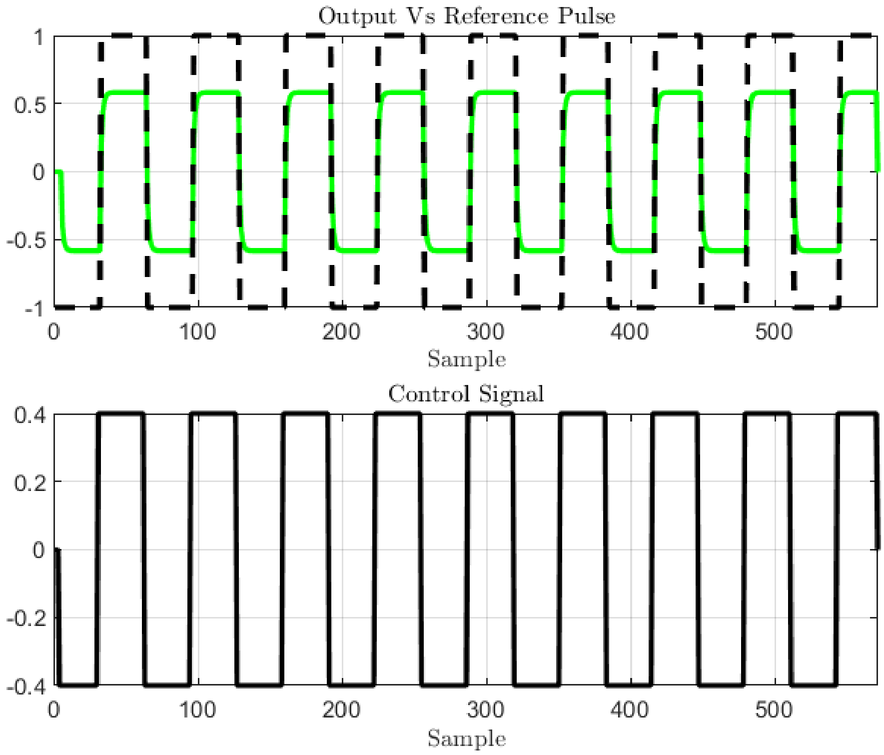

Figure 26. Output of system with delay change using J3 cost function

It is obvious that changing the delay value does not affect the results of the one-step ahead predictive controller using the J3 cost function, it suggests that the controller is almost robust to changes in the delay parameter. However, it is important to note that the specific behavior may depend on the characteristics of our system and controller implementation.

2.4 Constant future control

2.4.1 Without noise

In this problem, we have considered the prediction horizon 2 times the input delay, which because the input delay is 3 units, the prediction horizon is 6. In constant future control method, the control equation is as follows:

$$y_m(t+d) = (R_d^*(1) + \bar{R}_d^*(q^{(-1)})q^{(-1)})u(t) + G_d^*(q^{(-1)})y(t)$$

$$u(t) = \frac{y_m(t+d) - G_d^*(q^{-1})y(t)}{R_d^*(1) + \overline{R_d^*}(q^{-1})q^{-1}}$$

According to the above equations, the value of u is calculated and will change in each step. The result of the simulation in this case is shown in Figures 27 and 28.

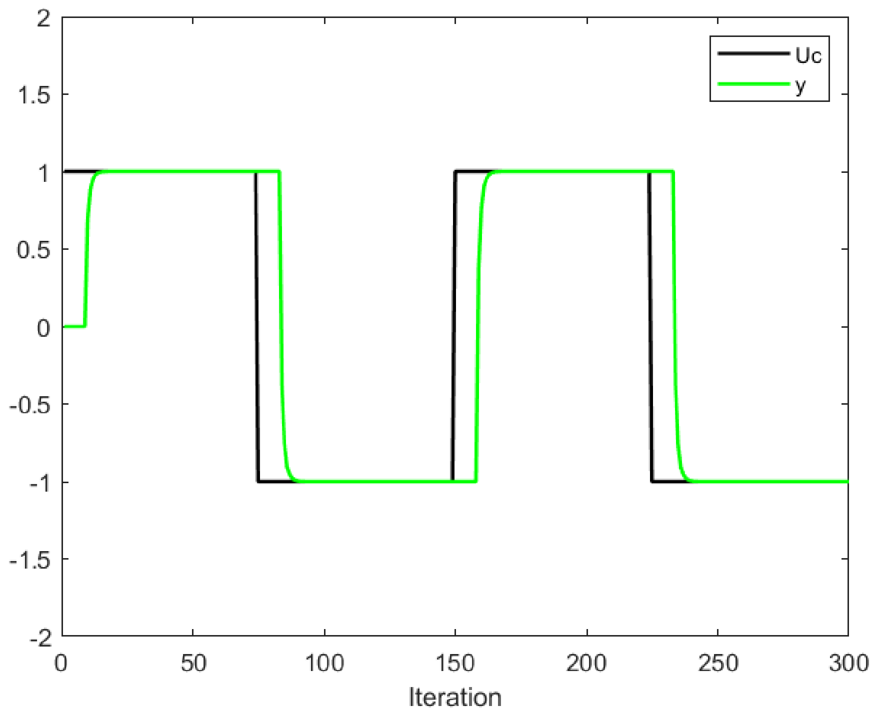

Figure 27. The output of the system with constant future control and without noise

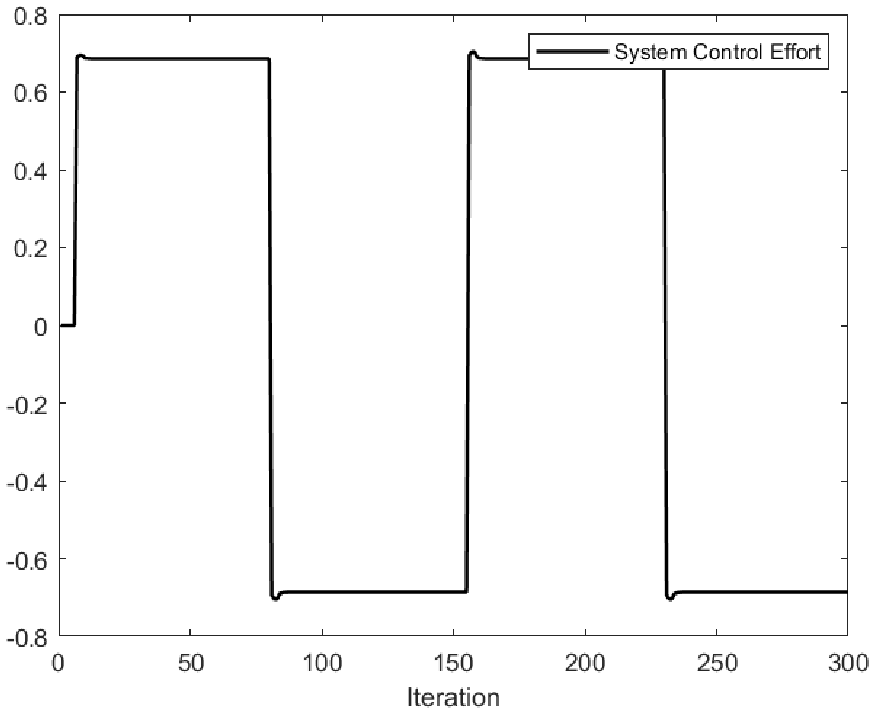

Figure 28. control effort of the system with constant future control and without noise

As it is clear from the Figures above, we have been able to do an almost good tracking. As we have considered the prediction horizon as 6, after 6 iterations, the output has tracked the reference signal with a small delay. Also, from Figure 28, we can see that there are not overshoots and undershoots in control effort and it shows a good performance.

2.4.2 With white noise

In this case, we have considered a white noise with zero mean and 0.01 variance in the output. In this case, the simulation results are as shown in Figures 29 and 30.

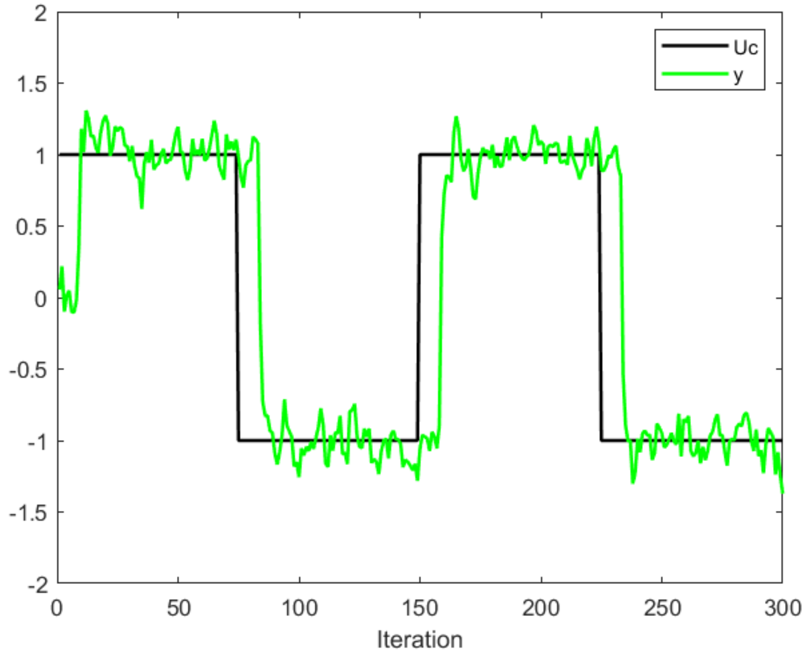

Figure 29. Output of the system with constant future control and with white noise

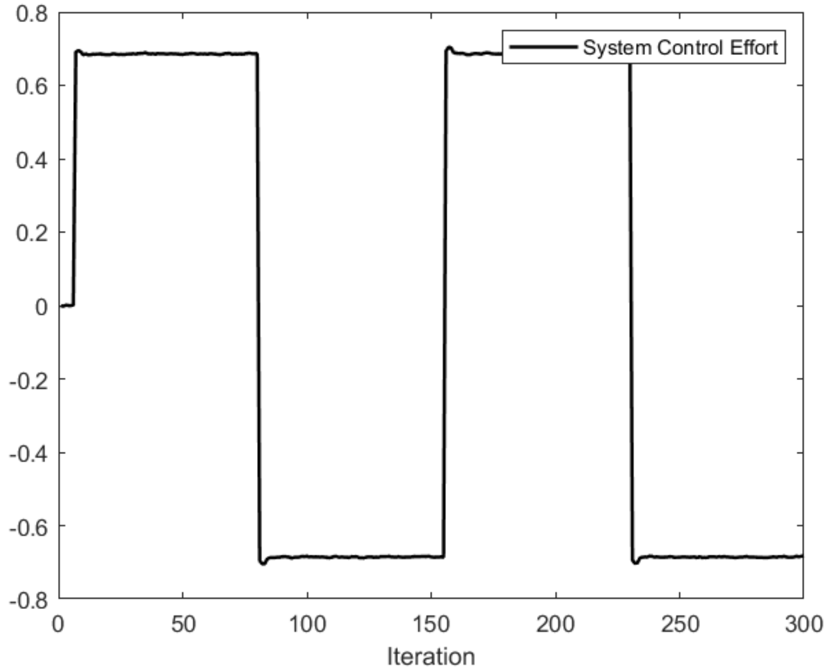

Figure 30. control effort of the system with constant future control and with white noise

As it is clear from the Figures above, the noise in the output has caused the output to fluctuate and increase the tracking error, and the designed controller has not shown good resistance to noise. The control effort shows a good response where no jumps can be see through the Figure 30.

2.4.3 With disturbance

In this case, all the design steps are the same as before, with the difference that in this case, in the 40th iteration, we have exerted a disturbance at the input of the system. Also, we have assumed that the incoming step disturbance has a delay equal to 3, like the input. The simulation results in this case are as shown in Figures 31 and 32.

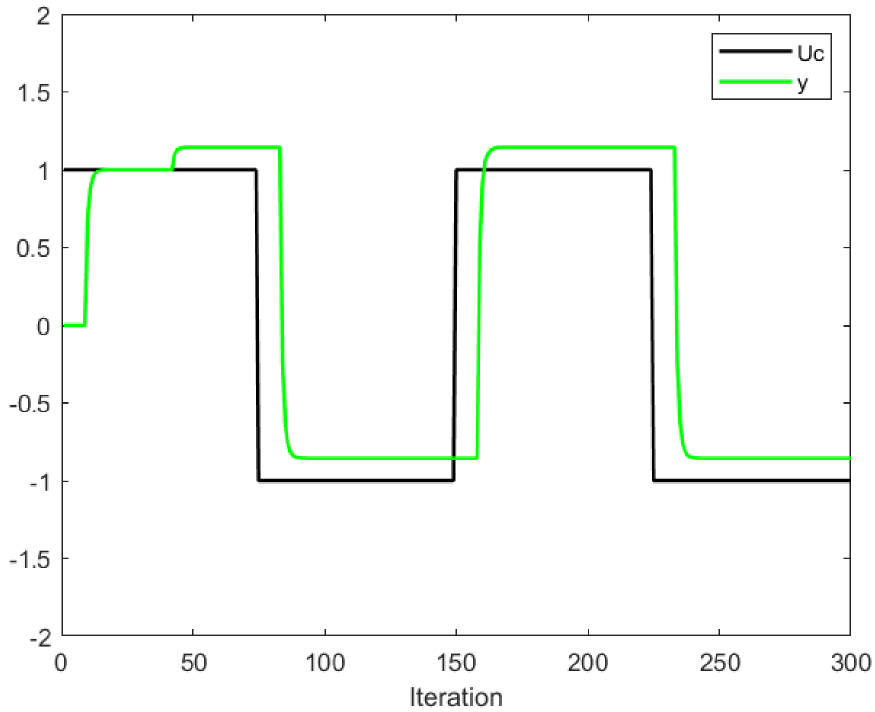

Figure 31. Output of the system with constant future control and with disturbance

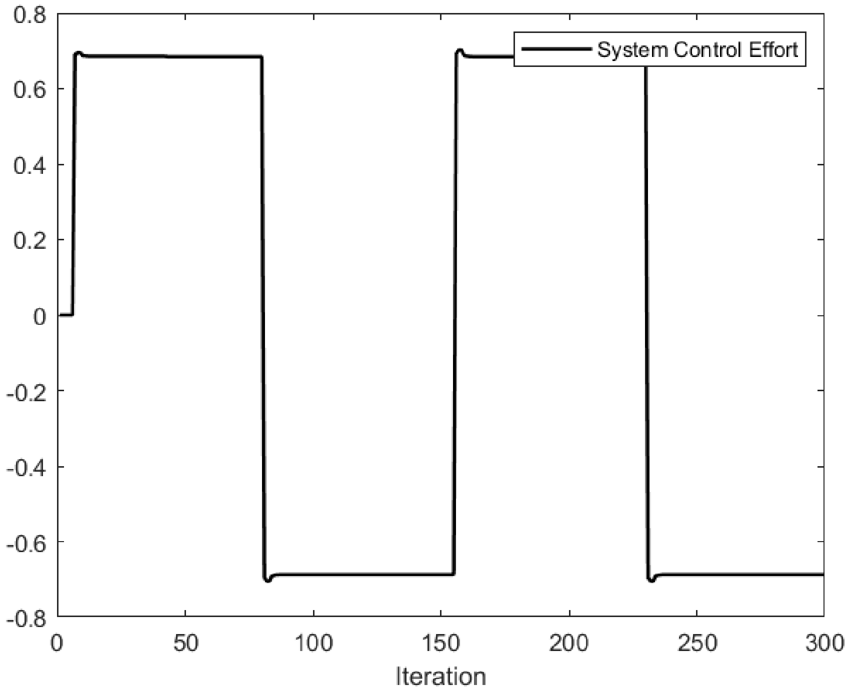

Figure 32. Control effort of the system with constant future control and with disturbance

As it is clear from the Figures above, the disturbance in the input has caused the response of the output of the system to shift as much and the prediction error of the output increases in the time of exerting the disturbance. It is clear that the controller has not been able to resist this disturbance and compensate the delay.

2.4.4 Delay change

If we design the controller with the same prediction horizon of 6 and then calculate the system output with a different delay instead of a delay of 3, the results will be as follows.

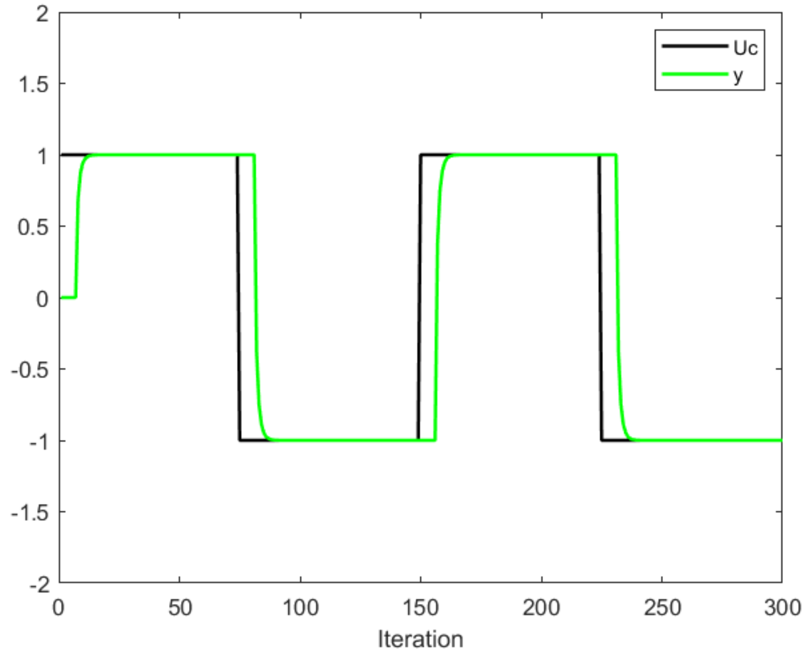

Figure 33. Output of the system with constant future control with delay change

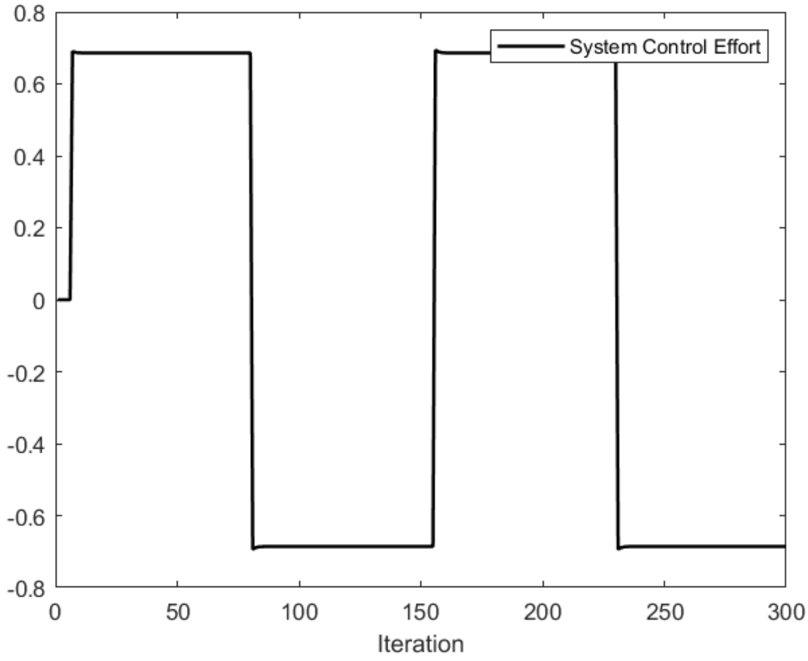

Figure 34. Control effort of the system with constant future control with delay change

As can be seen from the Figures 33 and 34, no significant changes could be observed in the results and the response is the same. So, the constant future controller was able to compensate the delay change.

3. Adaptive predictive controller

3.1 Estimation using RLS

Recursive Least Squares (RLS) estimation is a technique used in predictive controllers to estimate the parameters of a model that represents the system being controlled. The RLS estimation algorithm updates the model parameters recursively based on incoming data, allowing the controller to adapt and improve its predictions over time. In this section, the system model was considered as follows and by implementing the RLS algorithm, the results were obtained as given in Figures 35 and 36.

$$y(k) = [-\mathrm{y}(\mathrm{k}-1)\ \ -\mathrm{y}(\mathrm{k}-2)\ \mathrm{u}(\mathrm{k}-1)\ \mathrm{u}(\mathrm{k}-2)\ \mathrm{u}(\mathrm{k}-3)\ \mathrm{u}(\mathrm{k}-4)]\begin{bmatrix} a_1 \\ a_2 \\ b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix}$$

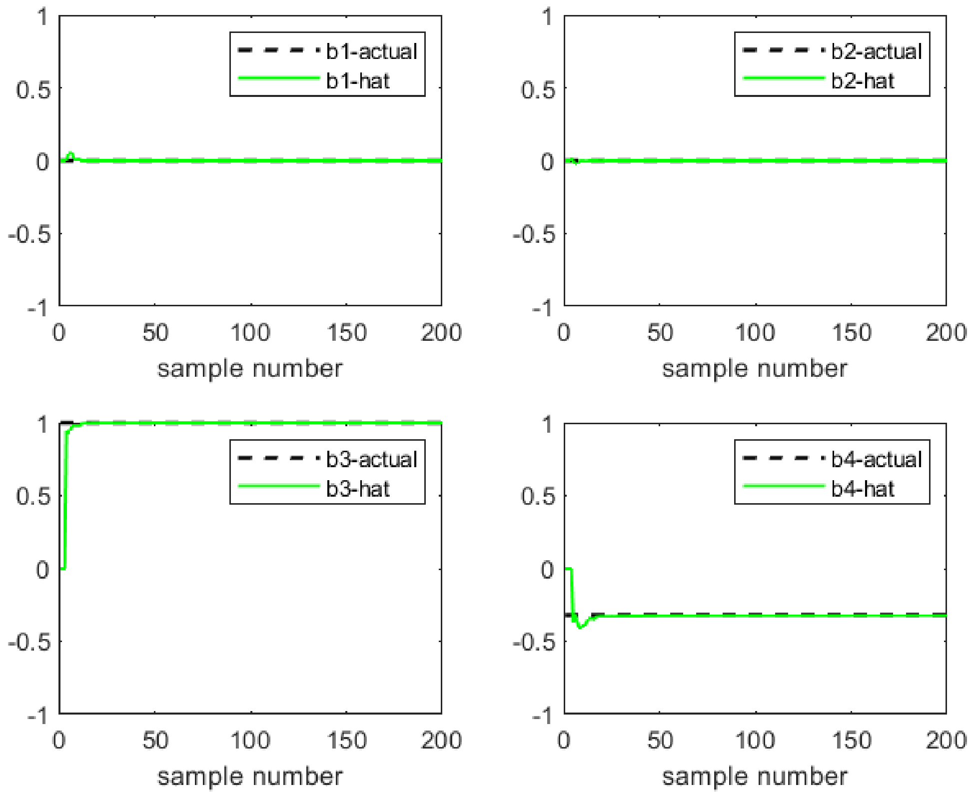

Figure 35. Estimation of nominator parameters using RLS algorithm

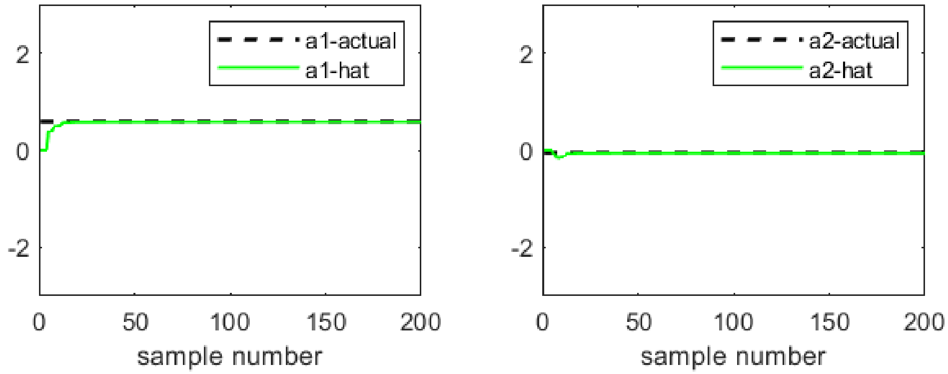

Figure 36. Estimation of denominator parameters using RLS algorithm

It can be seen that the first two parameters are zero, so the input delay is equal to 3. We can see from Figures 35 and 36 that nominator and denominator parameters were estimated accurately. So, using RLS method showed a proper performance in estimating the denominator and nominator parameters of the system with predictive controller.

3.2 Indirect adaptive

In this section, we will implement an indirect adaptive method to normal and weighted one-step ahead controllers, predictive controllers using J2 and J3 cost functions and finally, constant future controllers and discuss the results. Indirect adaptive controllers are a type of control system that adjust their parameters or structure based on feedback from the system they are controlling. Unlike direct adaptive controllers, which modify their control signals directly, indirect adaptive controllers adjust their internal parameters to optimize control performance.

The main idea behind indirect adaptive control is to use a mathematical model of the system being controlled to estimate its behavior and make adjustments accordingly. The adaptive controller uses the difference between the model's predictions and the actual system output to update its internal parameters.

3.2.1 One-step ahead

3.2.1.1 Without noise

In the case of one-step ahead controller without noise and disturbances, the results are shown in Figure 37.

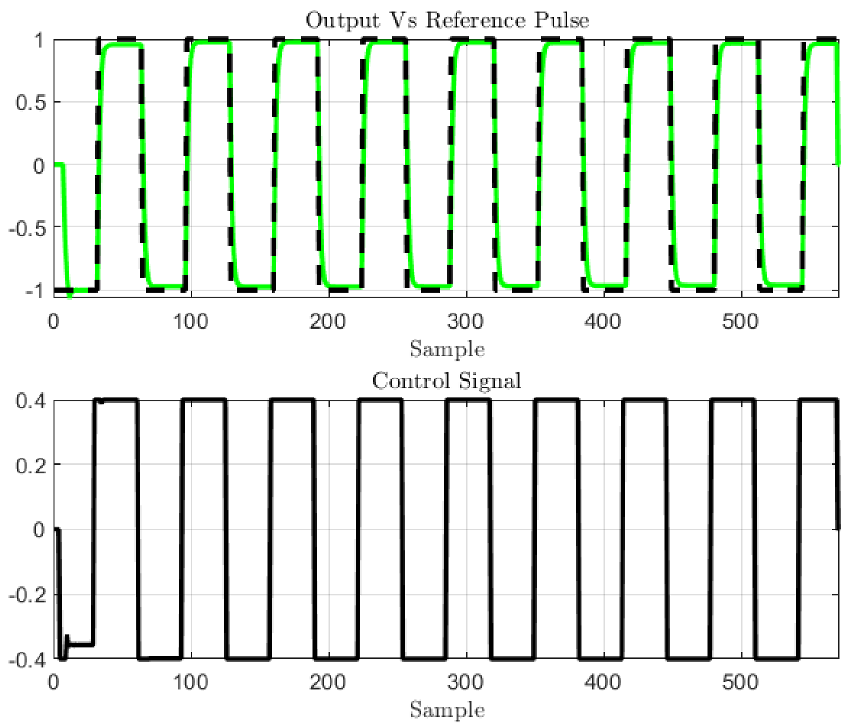

Figure 37. Output of system with indirect adaptive one-step ahead controller and without noise

We can see from Figure 37 that the output of our system, controlled by an indirect adaptive controller using the projection algorithm (PA) for estimation, is tracking the reference signal accurately and without any bias, it indicates that the controller is performing well.

The projection algorithm is commonly used in adaptive control to estimate the parameters of the system model. By continuously updating the model parameters based on the system's output and the reference signal, the adaptive controller can adjust its control signals to minimize the tracking error.

When the output of the system closely follows the reference signal, it suggests that the adaptive controller has successfully adapted its parameters to match the dynamics of the system. The absence of bias indicates that the controller has effectively compensated for any steady-state errors that might have been present initially.

It's important to note that the performance of an indirect adaptive controller can depend on various factors, such as the accuracy of the system model, the quality of the reference signal, and the presence of noise or disturbances. In this case, the absence of noise might contribute to the accurate tracking of the reference signal.

However, it's always recommended to evaluate the performance of the controller under different operating conditions, including the presence of noise and disturbances, to ensure its robustness and reliability in real-world scenarios. So, we will evaluate its performance under different conditions in the following sections.

If we take a closer look at Figure 37, we can see that initially, there is an overshoot in the output, and it cannot track the reference signal. The reason for this matter is that in the initial samples, the parameters of the system are not estimated correctly and the identification has not been performed yet. After a few samples, the output is capable of tracking the reference signal, indicating that the system parameters are accurately estimated.

3.2.1.2 With white noise

In the case of one-step ahead controller with white noise, the results are shown in Figure 38.

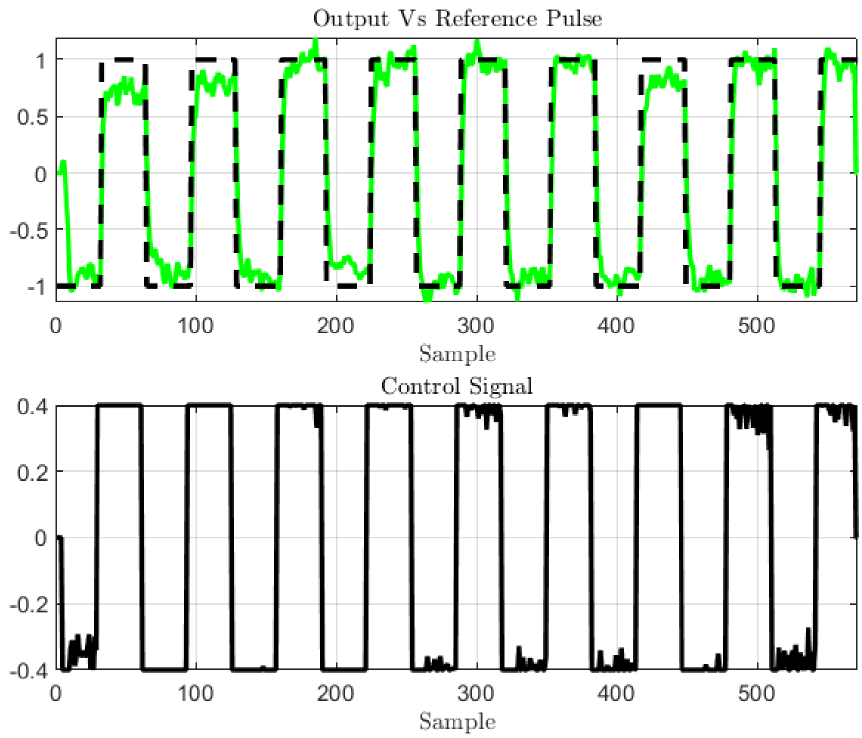

Figure 38. Output of system with indirect adaptive one-step ahead controller and with white noise

We can see from Figure 38 that our system's output is still able to track the reference signal reasonably well, albeit with some discrepancies, despite the presence of white noise, it indicates that the indirect adaptive controller is partially successful in compensating for the noise and maintaining tracking performance. White noise, being a random signal with equal power at all frequencies, can introduce unpredictable fluctuations in the system's output. The adaptive controller, based on its estimation and adaptation algorithms, tries to mitigate the effects of noise and maintain tracking as closely as possible to the reference signal.

However, due to the random nature of white noise, there will inevitably be instances where the output deviates from the reference signal. The level of noise and its impact on the tracking performance depend on several factors, including the amplitude of the noise, the dynamics of the system, and the adaptation capabilities of the controller.

It's normal to observe some degradation in tracking performance when white noise is present. The noise can introduce variability and affect the accuracy of the tracking. Moreover, the presence of noise in the output signal also resulted in a noisy output (y). The noise from the system output might propagate through the controller, potentially amplifying it. This can result in fluctuations and instability in the control signal, leading to a noisy output. To further improve the performance in the presence of noise, we could consider applying additional techniques such as filtering or signal processing methods to reduce the impact of noise on the control loop. These techniques can help in enhancing the tracking accuracy and reducing the noise in the output signal.

If we take a closer look at Figure 38, we can see that initially, there is an overshoot in the output, and it cannot track the reference signal. The reason for this matter is that in the initial samples, the parameters of the system are not estimated correctly and the identification has not been performed yet. After a few samples, the output is capable of tracking the reference signal, indicating that the system parameters are accurately estimated.

3.2.1.3 With disturbance

In the case of one-step ahead controller with disturbance at the input, the results are shown in Figure 39.

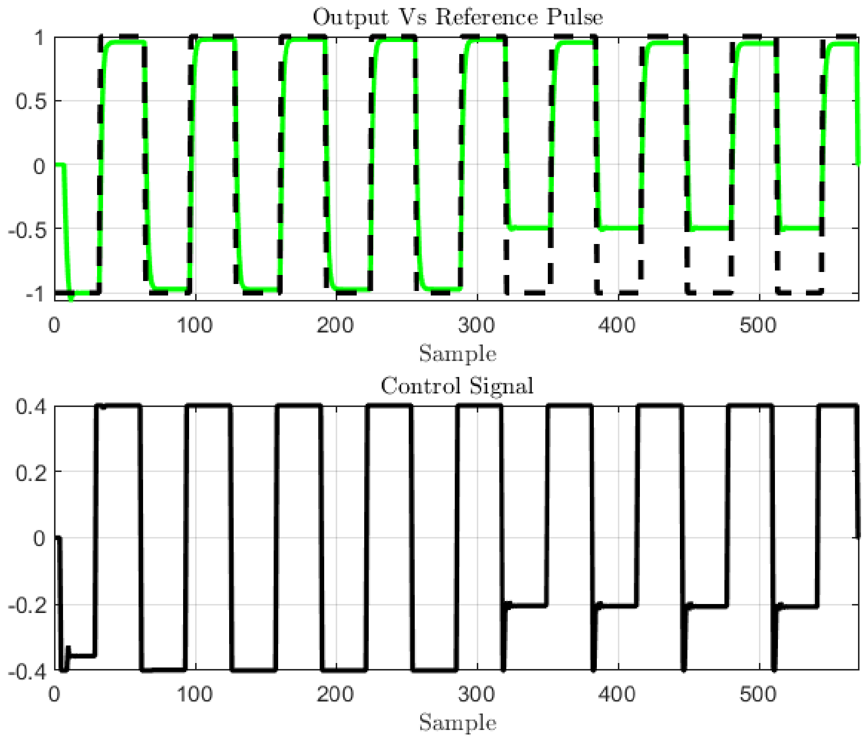

Figure 39. Output of system with indirect adaptive one-step ahead controller and with disturbance

As shown in Figure 39, as our system's output (y) is able to track the reference signal well before the disturbance is introduced but experiences a bias afterward that the controller cannot compensate for, it suggests that the indirect adaptive controller might have limitations in dealing with disturbances. Disturbances can be external inputs or variations that affect the system's behavior, potentially leading to deviations from the desired response. When a disturbance is introduced at the input, it can disrupt the system dynamics and cause the output to deviate from the reference signal. While indirect adaptive controllers are designed to adapt to changes in the system and minimize tracking errors, they may not always be able to completely compensate for disturbances. The effectiveness of an adaptive controller in dealing with disturbances depends on various factors, such as the type and magnitude of the disturbance, the accuracy of the system model, and the adaptation capabilities of the controller.

In our case, the bias that occurs after the disturbance suggests that the adaptive controller is unable to fully compensate for the disturbance's effects. The bias indicates a systematic error or offset between the desired output and the actual output. This could be due to limitations in the controller's adaptation mechanism or the disturbance's impact on the system dynamics.

3.2.1.4 Delay change

In the case of one-step ahead controller with delay change, the results are shown in Figure 40.

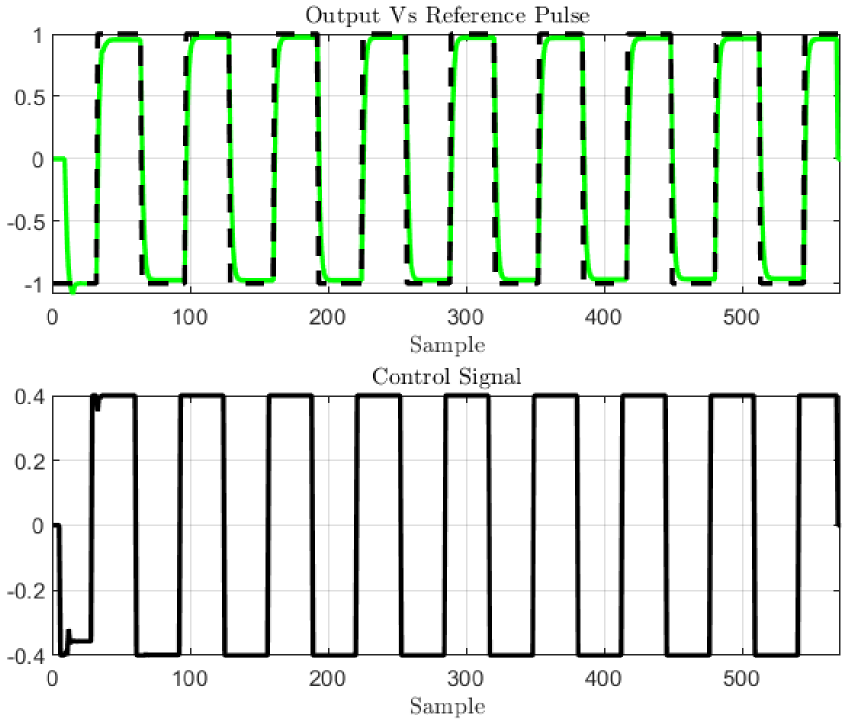

Figure 40. Output of system with indirect adaptive one-step ahead controller and with delay change

Changing the delay in the system does not result in significant changes in the performance of the indirect adaptive controller, so, it could indicate that the controller is relatively insensitive to delays. This can be seen as a positive characteristic as it implies robustness to time delays in the system.

3.2.2 Weighted one-step ahead

3.2.2.1 Without noise

In the case of weighted one-step ahead controller without noise, the results are represented in Figure 41.

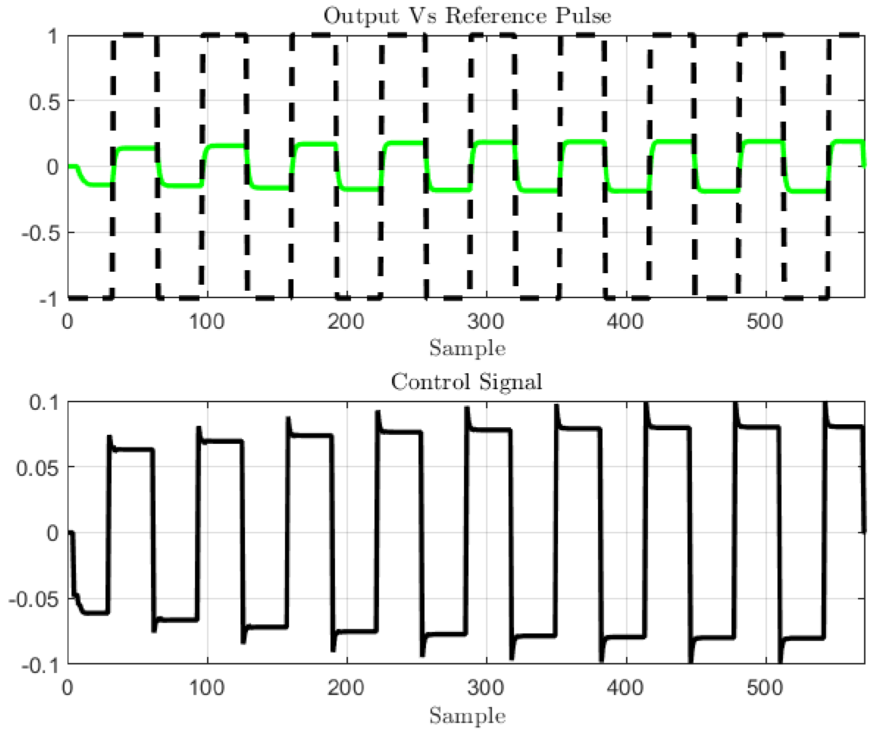

Figure 41. Output of system with indirect adaptive weighted one-step ahead controller and without noise

In the case of a weighted one-step ahead controller without noise, Figure 41 illustrates the performance of the system. Based on the information provided, it indicates that the output signal (y) follows or tracks the reference signal with a bias. This suggests that there might be a systematic deviation between the desired output and the actual output of the system.

Additionally, the figure suggests that as the number of samples increases, the control effort also increases. This implies that the controller needs to exert more effort or take stronger actions to drive the system towards the desired output as more data points are considered.

3.2.2.2 With white noise

In the case of weighted one-step ahead controller with white noise, the results are represented in Figure 42.

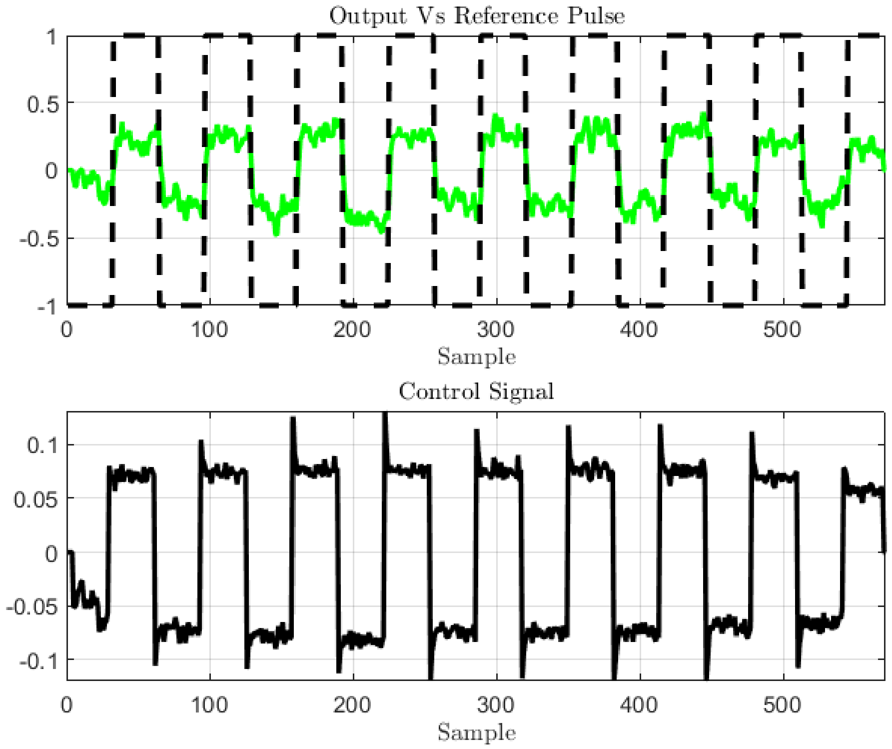

Figure 42. Output of system with indirect adaptive weighted one-step ahead controller and with white noise

In the case of a weighted one-step ahead controller with white noise, Figure 42 displays the results of the system. According to the given information, there are no substantial changes observed in terms of tracking between the cases with or without noise. This implies that the controller is still able to follow or track the reference signal reasonably well, despite the presence of noise.

However, when white noise is present at the output, the output signal (y) becomes noisy. This indicates that the noise introduced into the system affects the output signal and introduces random fluctuations or disturbances. The noise can degrade the quality of the output signal and potentially affect the overall performance of the system.

3.2.2.3 With disturbance

In the case of weighted one-step ahead controller with disturbance, the results are represented in Figure 43.

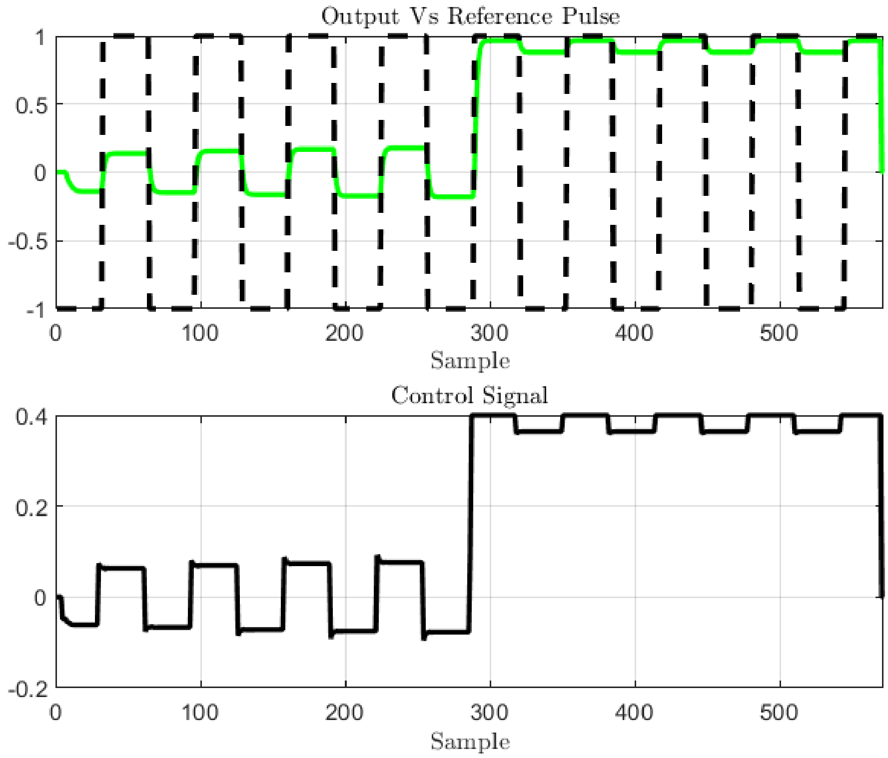

Figure 43. Output of system with indirect adaptive weighted one-step ahead controller and with disturbance

In the case of a weighted one-step ahead controller with a disturbance, Figure 43 illustrates the outcomes of the system. As per the provided information, a notable observation is made at the 300th sample, where a disturbance is introduced. At this point, a deviation in the output signal (y) and the control effort signal is observed, and it is not compensated.

This indicates that the disturbance has an adverse effect on the system's performance. The controller is unable to fully compensate for the disturbance, resulting in a deviation or error between the desired output and the actual output. The control effort signal, which represents the actions taken by the controller to regulate the system, also experiences a change or increase in response to the disturbance.

The inability to fully compensate for the disturbance at the 300th sample suggests a limitation in the controller's design or its ability to handle disturbances. It is important to note that mitigating disturbances and achieving robust control in the presence of external disturbances can be a challenging task, and the effectiveness of the controller depends on various factors, such as the disturbance characteristics and the controller's robustness.

3.2.2.4 Delay change

In the case of weighted one-step ahead controller with delay change, the results are represented in Figure 44.

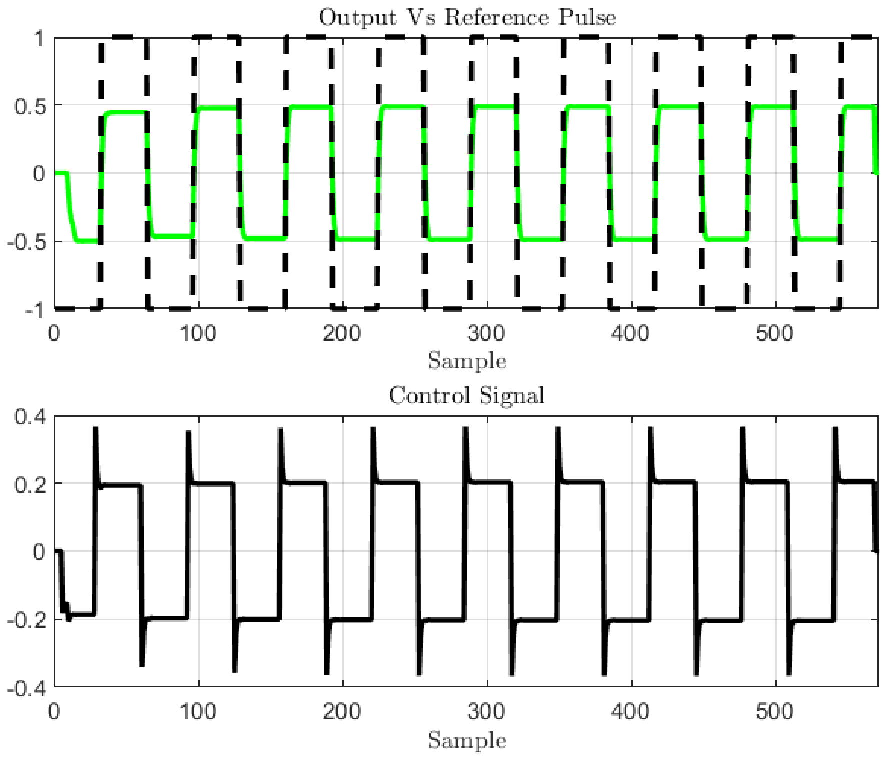

Figure 44. Output of system with indirect adaptive weighted one-step ahead controller and with delay change

In the case of a weighted one-step ahead controller with a delay change, Figure 44 depicts the outcomes of the system. We can see that the delay change does not appear to significantly affect the system's tracking behavior. This suggests that the controller is resilient to variations in the delay parameter and can still maintain reasonable tracking performance.

Initially, when the parameters are not yet identified by the Projection Algorithm (PA) estimation method, the tracking does not occur. This indicates that without accurate knowledge of the system's parameters, the controller is unable to properly track the reference signal. However, after the estimation of parameters using the PA estimation method, the tracking performance improves.

This suggests that the PA estimation method is effective in identifying the system's parameters and enabling the controller to adapt accordingly, resulting in better tracking performance.

3.2.3 One-step ahead using J2 and J3

3.2.3.1 J2

3.2.3.1.1 Without noise

In the case of one-step ahead controller using J2 cost function and without noise, the results are shown in Figure 45.

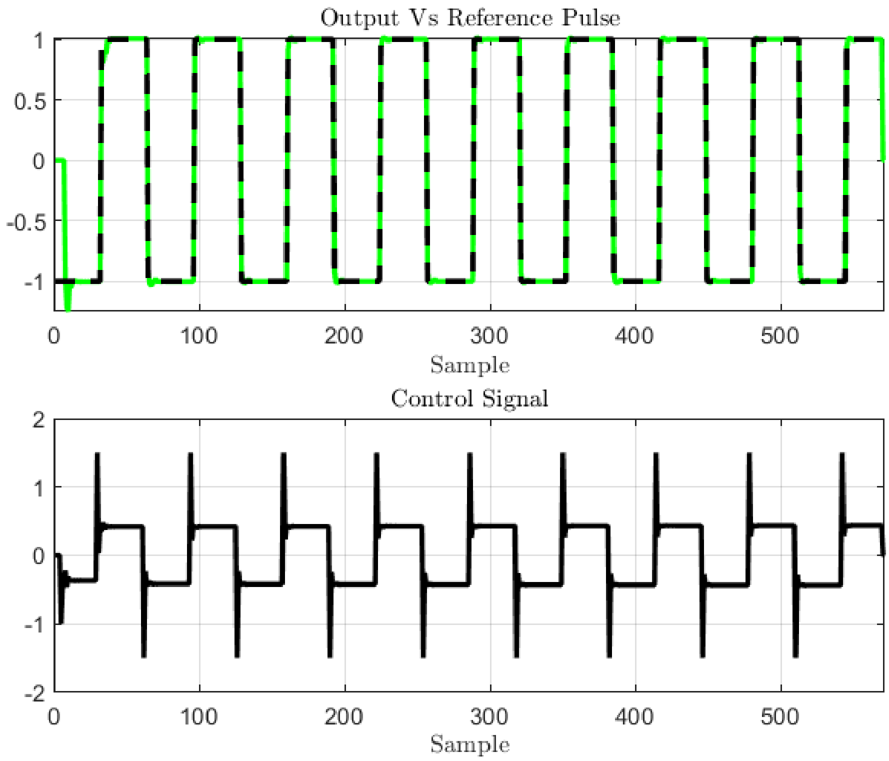

Figure 45. Output of system with indirect adaptive J2 one-step ahead controller and without noise

In the case of a one-step ahead controller using the J2 cost function and without noise, Figure 45 displays the results of the system. Based on the provided information, there are several observations to note:

1. Initially, when the parameters are not yet identified by the Projection Algorithm (PA) estimation method, the tracking does not occur. This indicates that without accurate

knowledge of the system's parameters, the controller is unable to properly track the reference signal. However, after parameter estimation using the PA method, the tracking performance improves.

2. After parameter estimation, the tracking is performed in the best way, with the output signal (y) completely fitting the reference signal. This suggests that the controller is able to closely follow or track the desired output without significant deviations.
3. The control effort is acceptable, indicating that the controller is able to regulate the system adequately. However, some overshoot and undershoots are observed in the control effort signal. This implies that the controller's response might exhibit temporary deviations beyond the desired range before settling down.

3.2.3.1.2 With white noise

In the case of one-step ahead controller using J2 cost function and with white noise, the results are shown in Figure 46.

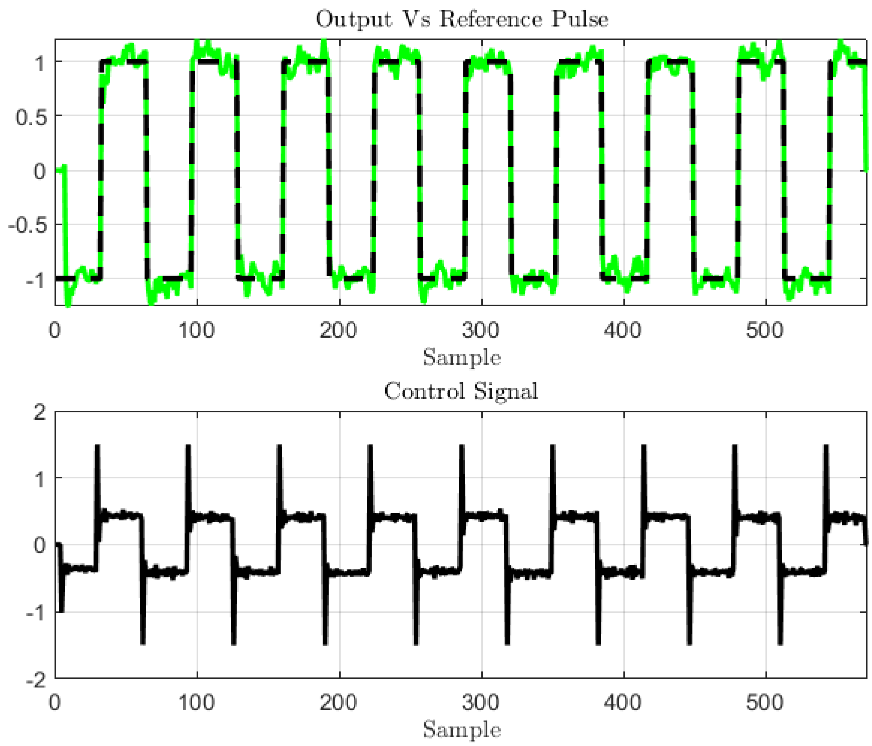

Figure 46. Output of system with indirect adaptive J2 one-step ahead controller and with white noise

In the case of a one-step ahead controller using the J2 cost function and with white noise, Figure 46 presents the results of the system. According to the provided information, the performance of the system is similar to the case without noise, with the exception that the output signal (y) is noisy in this case.

This suggests that the controller is still able to track the reference signal reasonably well, despite the presence of white noise. However, the noise introduced into the system affects the output signal, leading to random fluctuations or disturbances in the measured output.

While the tracking behavior remains similar to the noise-free case, the presence of noise can degrade the quality of the output signal. The noise can introduce variability and make it challenging to obtain a clean and precise representation of the desired output.

3.2.3.1.3 With disturbance

In the case of one-step ahead controller using J2 cost function and with disturbance, the results are shown in Figure 47.

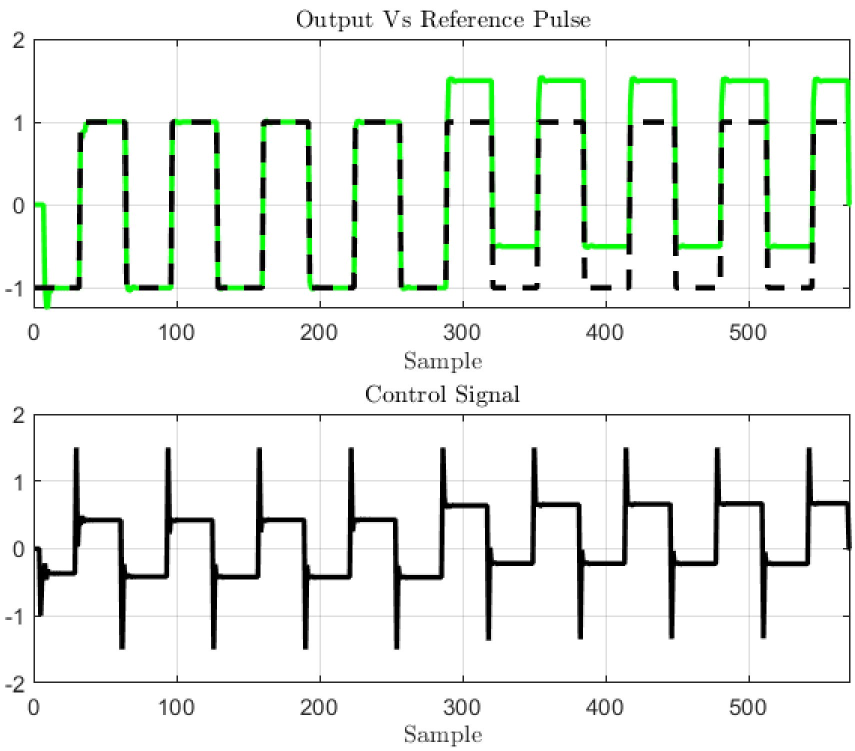

Figure 47. Output of system with indirect adaptive J2 one-step ahead controller and with disturbance

In the case of a one-step ahead controller using the J2 cost function and with a disturbance, Figure 47 illustrates the results of the system. According to the provided information, several observations can be made:

1. When the disturbance is introduced to the system at the 300th sample, a bias occurs in the output signal (y) and reference signal. This bias indicates a deviation or offset between these signals, suggesting that the disturbance has disrupted the tracking behavior of the controller. The output signal is no longer in perfect alignment with the reference signal.
2. However, in the case of the control effort signal, no visible changes are observed before and after the disturbance is introduced. This suggests that the control effort remains relatively unaffected by the disturbance. The controller is still exerting similar control actions to regulate the system, despite the disturbance's impact on the output and reference signals.

It's important to note that disturbances can have various effects on a system, and the behavior of the controller and its response to disturbances depend on the specific control strategy and design.

3.2.3.1.4 Delay change

In the case of one-step ahead controller using J2 cost function and with delay change, the results are shown in Figure 48.

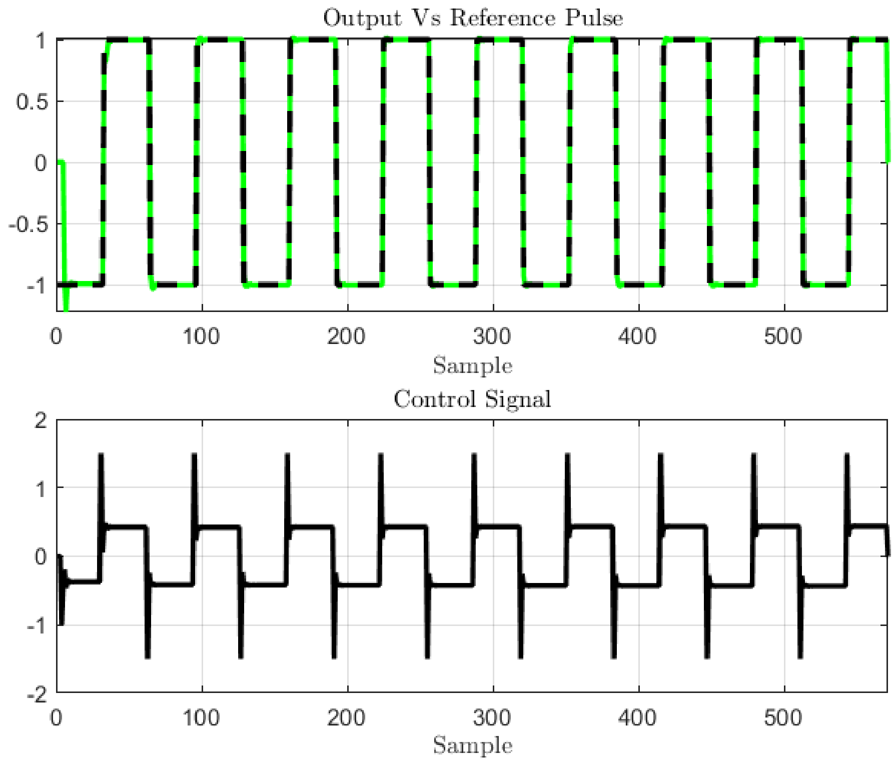

Figure 48. Output of system with indirect adaptive J2 one-step ahead controller and with delay change

In the case of a one-step ahead controller using the J2 cost function and with delay change, Figure 48 represents the results of the system. Based on the provided information, several observations can be made:

1. The delay change does not result in significant changes in the system's behavior. This suggests that the controller is robust to variations in the delay parameter and can maintain a high level of tracking performance despite the changes in delay.
2. After parameter estimation using the Projection Algorithm (PA) estimation method, the tracking performance improves significantly. The output signal (y) aligns perfectly with the reference signal, indicating that the controller can accurately track the desired output.
3. The control effort is acceptable, indicating that the controller can effectively regulate the system. However, some overshoot and undershoots are observed in the control

effort signal. This suggests that the controller's response might exhibit temporary deviations beyond the desired range before settling down, similar to the case mentioned before.

3.2.3.2 J3

3.2.3.2.1 Without noise

In the case of one-step ahead controller using J3 cost function and without noise, the results are shown in Figure 49.

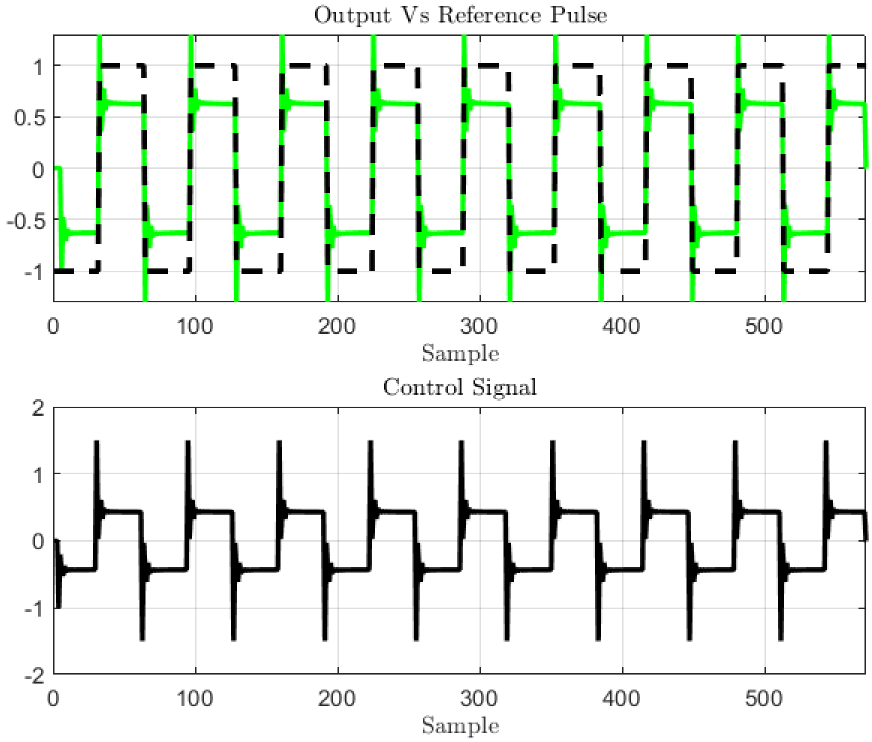

Figure 49. Output of system with indirect adaptive J3 one-step ahead controller and without noise

In the case of a one-step ahead controller using the J3 cost function and without noise, Figure 49 depicts the results of the system. According to the provided information, several observations can be made:

1. The tracking performance is deemed acceptable, suggesting that the controller is able to follow the reference signal to a reasonable extent. However, a bias exists between the output signal (y) and the reference signal, indicating a systematic deviation between the desired output and the actual output of the system.

2. Some overshoots and undershoots are observed in the output signal (y). This indicates that the controller's response exhibits temporary deviations beyond the desired range, both exceeding and falling short of the reference signal, before settling down.
3. Similar overshoots and undershoots can also be seen in the control effort signal. This suggests that the controller is exerting varying control actions to regulate the system, resulting in fluctuations in the control effort signal.

3.2.3.2.2 With white noise

In the case of one-step ahead controller using J3 cost function and with white noise, the results are shown in Figure 50.

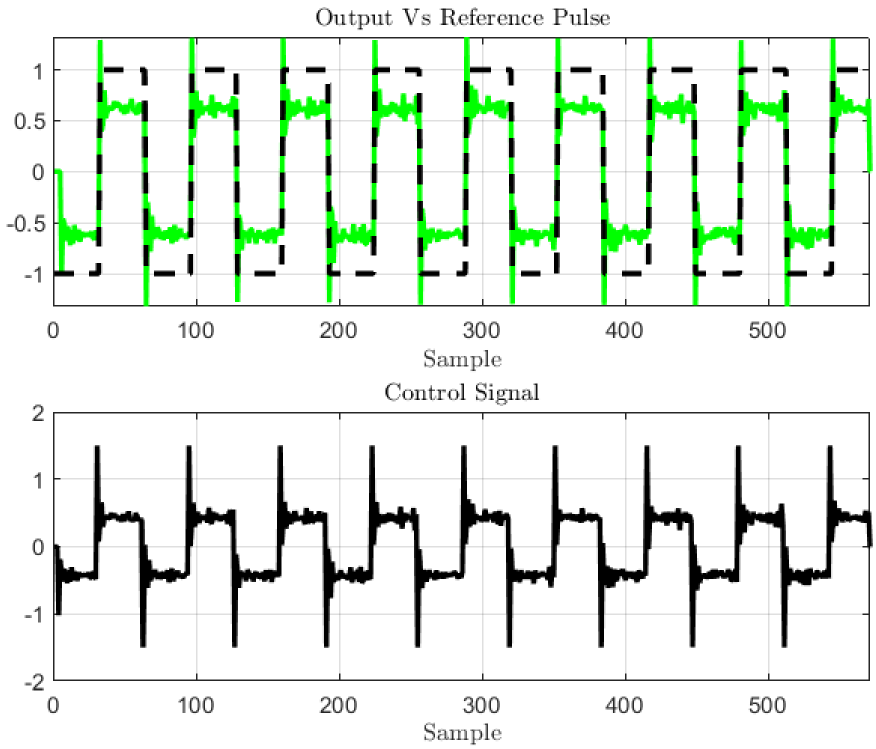

Figure 50. Output of system with indirect adaptive J3 one-step ahead controller and with white noise

In the case of a one-step ahead controller using the J3 cost function and with white noise, Figure 50 represents the results of the system. According to the provided information, the following observations can be made:

1. The output signal in this case becomes noisy due to the presence of white noise. The noise introduces random fluctuations or disturbances into the measured output, leading to a degraded quality of the output signal.
2. Despite the presence of noise, the tracking performance remains relatively unchanged with negligible changes. This suggests that the controller is still able to track the reference signal reasonably well, despite the noise-induced variability in the output signal. The controller adapts to the noise and maintains its ability to follow the desired output.

3.2.3.2.3 With disturbance

In the case of one-step ahead controller using J3 cost function and with disturbance, the results are shown in Figure 51.

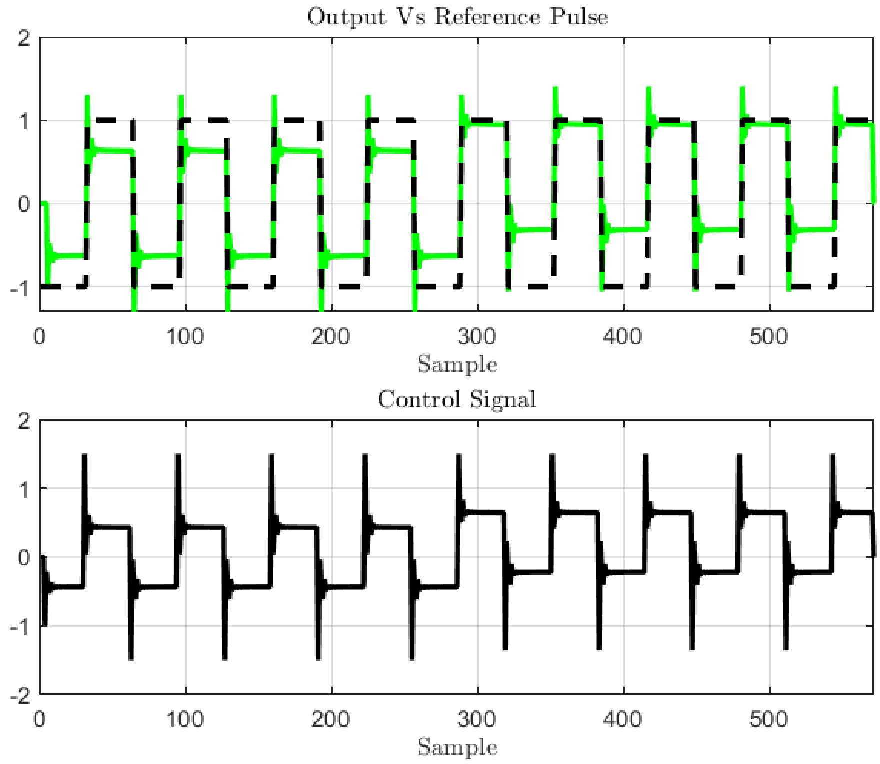

Figure 51. Output of system with indirect adaptive J3 one-step ahead controller and with disturbance

In the case of a one-step ahead controller using the J3 cost function and with a disturbance, Figure 51 illustrates the results of the system. According to the provided information, the following observations can be made:

After the disturbance is exerted at the 300th sample, the output tracking is not significantly changed. This suggests that the controller is able to maintain its tracking performance despite the presence of the disturbance. The output signal continues to closely follow the reference signal. Additionally, the control effort signal remains the same as before the disturbance was introduced. This implies that the controller's response, in terms of the control effort, is not affected by the disturbance. The controller is still exerting similar control actions to regulate the system, even in the presence of the disturbance.

These observations indicate that the controller, based on the J3 cost function, is robust to disturbances and can maintain satisfactory tracking performance despite the disturbance's presence.

3.2.3.2.4 Delay change

In the case of one-step ahead controller using J3 cost function and with delay change, the results are shown in Figure 52.

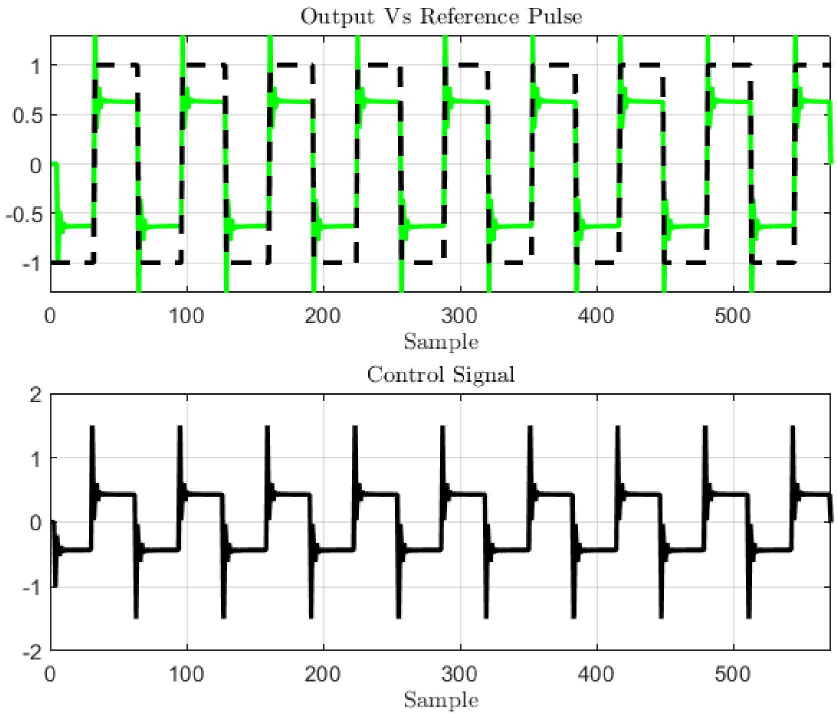

Figure 52. Output of system with indirect adaptive J3 one-step ahead controller and with delay change

In the case of a one-step ahead controller using the J3 cost function and with delay change, Figure 52 depicts the results of the system. Based on the results, the following observations can be made:

When the delay value is changed, the response of the system remains the same as it was under normal conditions. This suggests that the controller is robust to variations in the delay parameter and can maintain consistent performance despite changes in delay. It implies that the controller is able to track the reference signal and regulate the system effectively, irrespective of the delay value.

3.2.4 Constant future control

3.2.4.1 Without noise

In the case of one-step ahead controller with constant future control and without noise, the results are given in Figures 53 and 54.

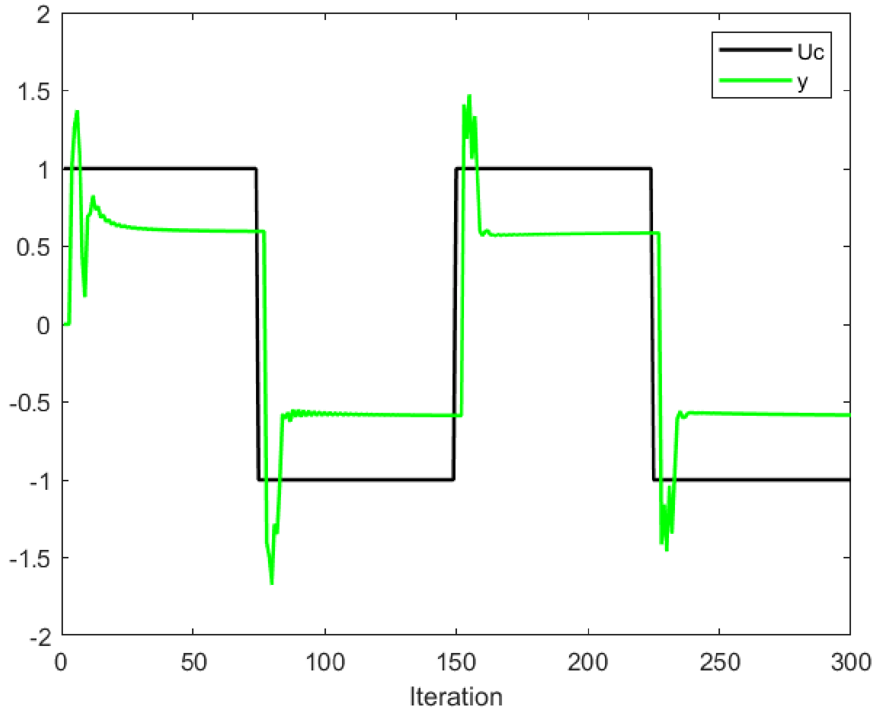

Figure 53. Output of system with indirect adaptive predictive constant future controller and without noise

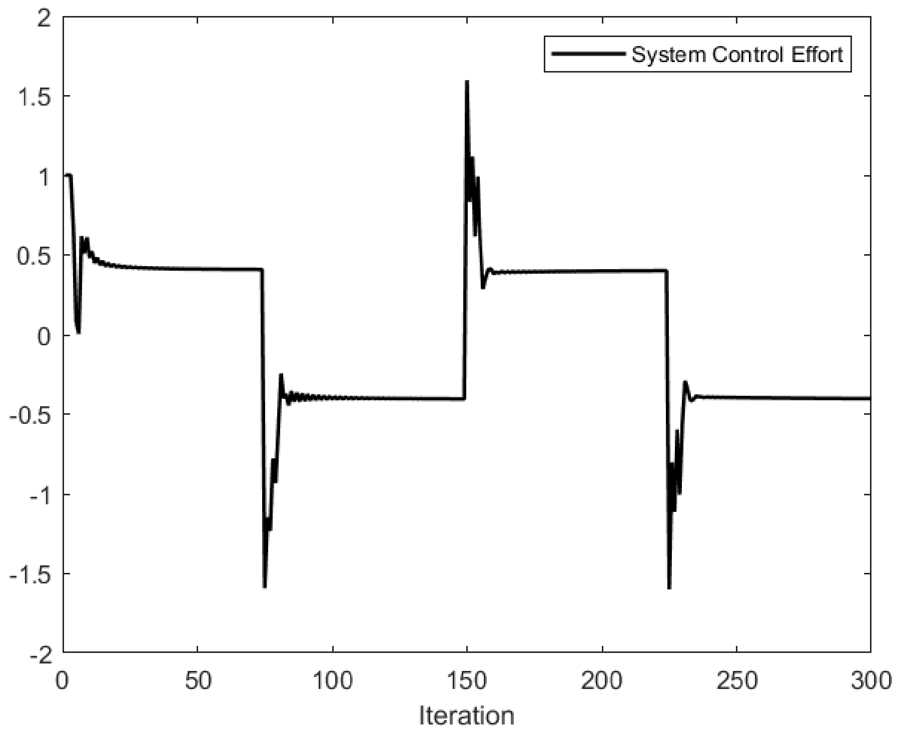

Figure 54. Control effort of system with indirect adaptive predictive constant future controller and without noise

In the case of a one-step ahead controller with constant future control and without noise, the system's results are depicted in Figures 53 and 54. Figure 53 reveals that the tracking performance is relatively good, as the controller is able to almost closely follow the reference signal. However, some small overshoots and undershoots can be observed in the output signal. These temporary deviations beyond the desired range indicate slight differences between the output signal and the reference signal.

Figure 54, on the other hand, presents the control effort signal. It demonstrates that the controller's control actions are generally acceptable in regulating the system. Similar to Figure 53, some overshoots and undershoots can be seen in the control effort signal. These deviations imply that the controller's response may exhibit temporary fluctuations beyond the desired control effort range before stabilizing.

It is important to note that the specific characteristics and behavior of the one-step ahead controller with constant future control play a significant role in the system's performance. The observed overshoots and undershoots in both the output signal and control effort signal may be inherent to the chosen control strategy or the specific dynamics of the controlled system.

3.2.4.2 With white noise

In the case of one-step ahead controller with constant future control and with white noise, the results are given in Figures 55 and 56.

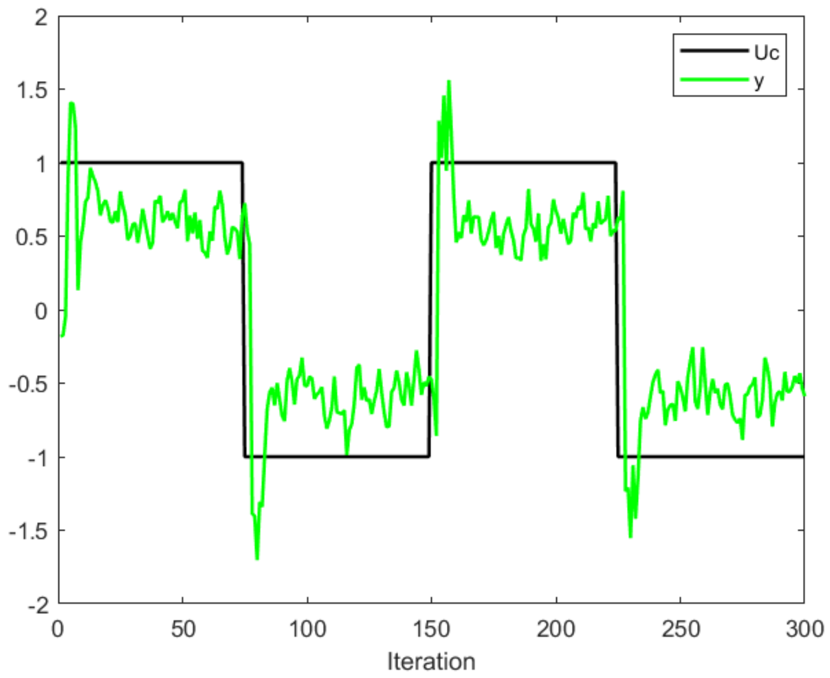

Figure 55. Output of system with indirect adaptive predictive constant future controller and with white noise

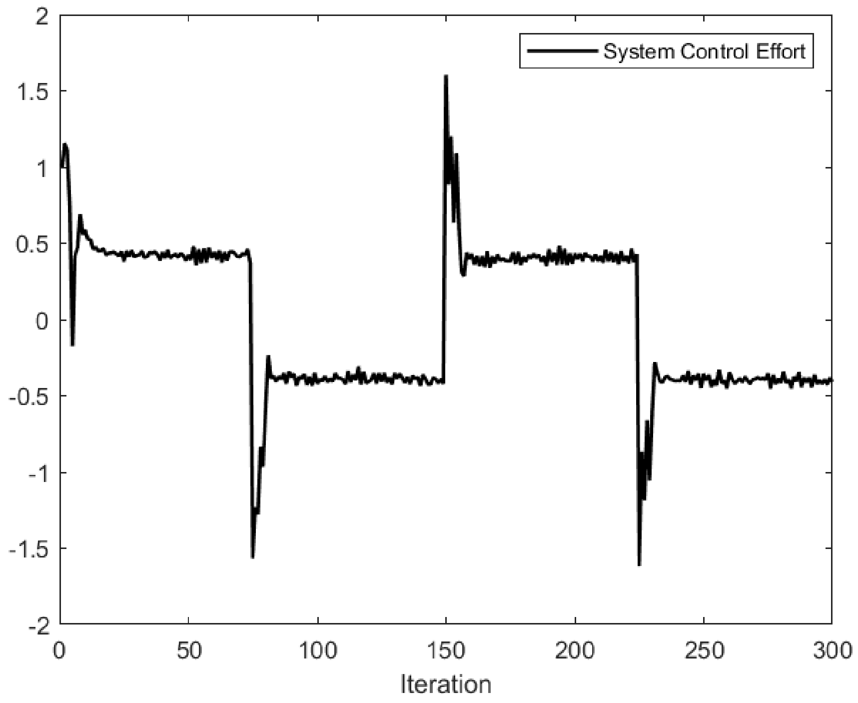

Figure 56. Control effort of system with indirect adaptive predictive constant future controller and with white noise

In the case of a one-step ahead controller with constant future control and with white noise, the system's results are presented in Figures 55 and 56. Figure 55 reveals that the tracking performance remains unchanged compared to the case without noise. This indicates that the controller is still capable of closely following the reference signal, regardless of the presence of white noise. Despite the noise-induced variability, the controller maintains its ability to track the desired output.

However, in Figure 56, it becomes evident that the output signal (y) becomes noisy due to the presence of white noise. The noise introduces random fluctuations or disturbances into the measured output, resulting in a degraded quality of the output signal. The noise-induced variability can make it challenging to obtain a clean and precise representation of the desired output. It's important to acknowledge that the presence of noise can impact the quality and reliability of the output signal. However, in this particular case, although the output signal becomes noisy, the controller is still able to maintain its tracking capability. The ability of the controller to mitigate the effects of noise on the tracking performance showcases its robustness in the presence of disturbances.

3.2.4.3 With disturbance

In the case of one-step ahead controller with constant future control and with disturbance, the results are given in Figures 57 and 58.

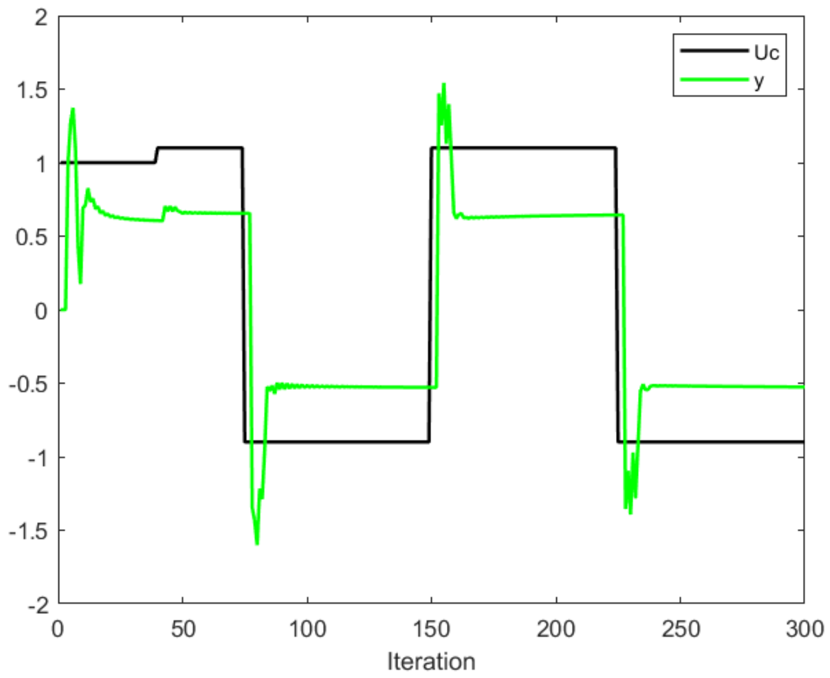

Figure 57. Output of system with indirect adaptive predictive constant future controller and with disturbance

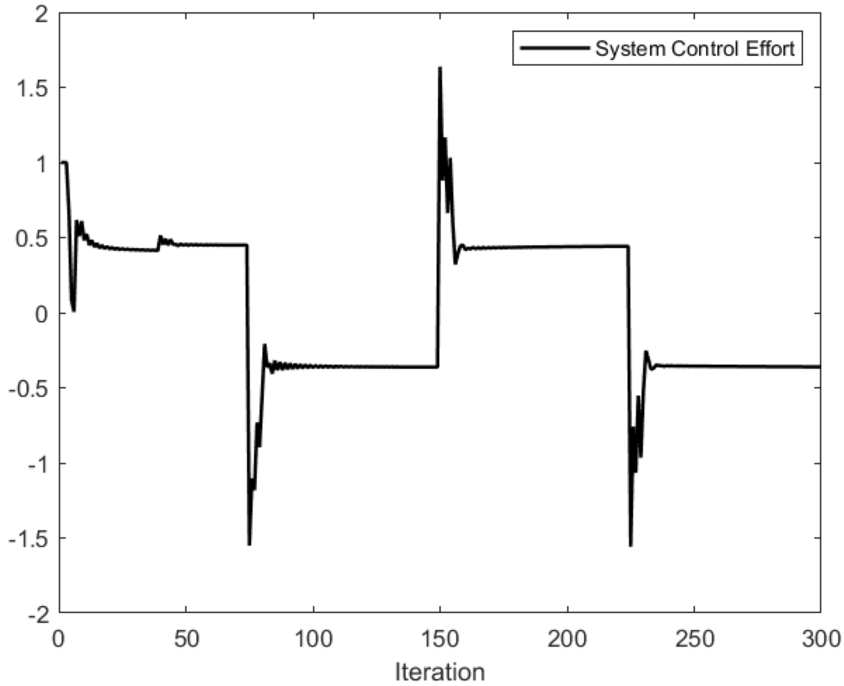

Figure 58. Control effort of system with indirect adaptive predictive constant future controller and with disturbance

In the case of a one-step ahead controller with constant future control and with disturbance, the results are depicted in Figures 57 and 58. Figure 57 shows that after the disturbance is exerted into the system, the controller demonstrates its ability to compensate for the disturbance. As a result, the output signal (y) is able to track the reference signal just as it did before the disturbance was introduced. This indicates that the controller dynamically adjusts its actions to counteract the impact of the disturbance, ensuring that the output remains aligned with the desired reference signal.

Similarly, Figure 58 illustrates that the control effort is also effectively compensated for the disturbance. The controller adapts its control actions to regulate the system, even in the presence of disturbances. This compensation mechanism ensures that the control effort remains within acceptable bounds, allowing for stable and accurate control of the system.

These results highlight the robustness and adaptability of the one-step ahead controller with constant future control. The controller's ability to compensate for disturbances and maintain tracking performance underscores its effectiveness in dynamic environments. By dynamically adjusting its actions based on the disturbance, the controller ensures that the output tracks the reference signal while also keeping the control effort under control.

3.2.4.4 Delay change

In the case of one-step ahead controller with constant future control and with delay change, the results are given in Figures 59 and 60.

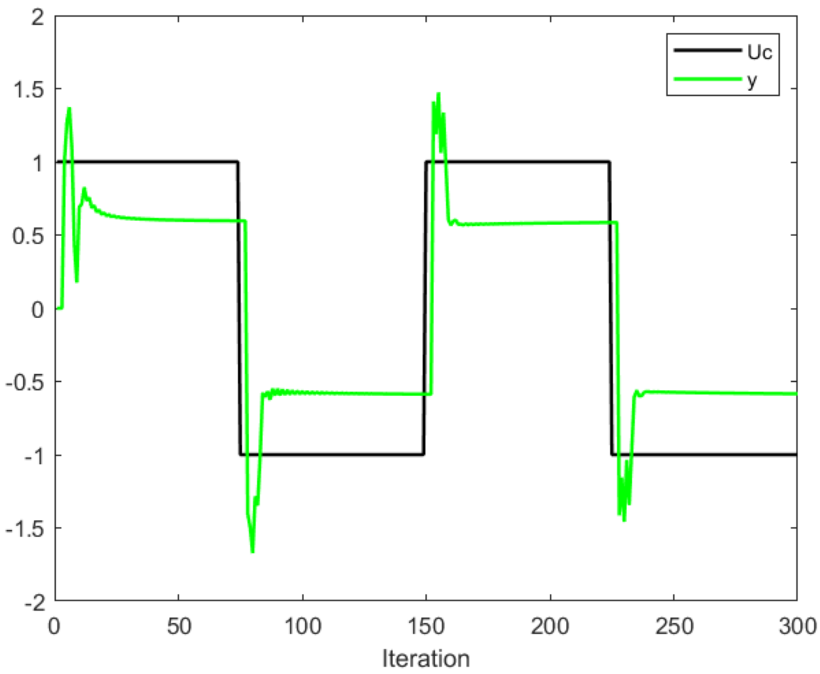

Figure 59. Output of system with indirect adaptive predictive constant future controller and with delay change

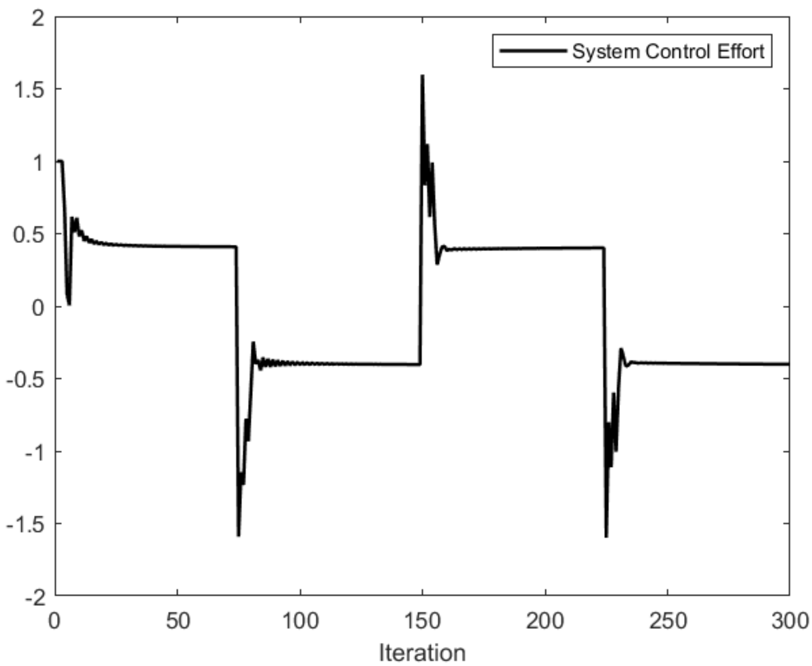

Figure 60. Control effort of system with indirect adaptive predictive constant future controller and with delay change

In the case of a one-step ahead controller with constant future control and with delay change, the results are shown in Figures 59 and 60. The findings reveal that no significant changes are observed in the system's behavior when the delay parameter is varied.

Figure 59 indicates that the tracking performance, represented by the output signal (y), remains consistent despite the delay change. The controller is able to maintain its ability to accurately track the reference signal, similar to the case without the delay change. This demonstrates the robustness of the controller to variations in the delay parameter.

Figure 60 further supports this observation, as the control effort signal shows no significant changes before and after the delay change. This suggests that the controller's response, in terms of the control effort, remains relatively unaffected by the delay variation. The controller continues to exert appropriate control actions to regulate the system, regardless of the delay change.

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Thanks for your Time

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